Fracture Toughness and Fatigue Behaviour of Materials- A Review.

MASTER THESIS

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by

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To my Mother and Father

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Abstract

This review will investigate fracture toughness and fatigue behaviour of materials, and also study of different parameters which have comprehensive effects on the fracture in both alloys and metals. These factors including temperature, stress, air and other environmental factors. It has found out that fatigue crack growth is a fertile area in order to do more tests on this topic. The efforts will be concentrated on investigation of the effects of temperature on fatigue and fatigue crack growth analysis in different conditions.

A large number of work has been done, particularly during the last 40 years, to study the related of high temperature low cycle fatigue data with difference factors. This work has manifested itself with the establishment of no less than 31 various correlation factors. These factors attempt, in varying ways, to predict the influences of temperature, strain rate, wave shape, and other factors upon the fatigue lives of difference materials. All of these factors create a big problem for the designer when trying to decide how to best design a component or structure, and what material to use.

Fracture of Metals

Fracture of metals:

When a soild part separates into two or more parts under stress, the process is called fracture. In engineering applications metal fractures can be classified as brittle and ductile, or it can be a combination of these two. Extensive plastic deformation in metal cause to ductile fracture, which is usually defined as a slow crack propagation. On the other hand, brittle fractures are defined as rapid crack propagation, and usually occur along characteristic crystallographic planes called cleavage planes. Many metals with the HCP crystal structure indicate brittle fractures due to limitations in the number of slip planes. A zinc single crystal under a high stress will fracture in a brittle manner. It is the same for body center cubic (BCC) metals such as α iron, molybdenum, and tungsten, which show brittle fractures at low temperature and high strain rates.

Brittle Fracture:

Brittle fracture happens with a small or no preceding plastic deformation. It happens, usually at unknown levels of stress, by the sudden propagation of a crack. The degree of brittle fracture is differes from material to another, for example some materials are totally brittle like glass and glassy ploymers; in crystalline materials, some plastic deformation precedes brittle fracture. Most brittle fractures are transgranular in most metals with polycrystalline structure, which means the cracks propagate across the matrix of the grains. Three stages can be noticed in the brittle fracture process in the metals.

- Plastic deformation which concentrates dislocations along slip planes at obstaches.
- Formation of shear stress due to the nucleatetion of micro-cracks in the area where dislocations are blocked.
- Propagation of micro-cracks due to further stress and store elastic strain energy.

Temperture, high strain rates and uniaxial state of stress lead to brittle fracture

Griffith Theory:

The first explanation given for the discrepancy between the theoretical strength and actual fracture strength in totally brittle materials was studied by Griffith. He implemented that in a brittle material there are many small ellipitical cracks as shown in Figure (30). And there is a strong concentration of stress at the tip of such an elliptical crack, and the value of the highest stress can be calculate as

- $m \approx 2\sigma\,(c/\rho)^{1/2}$

- m = maximum stress at the tip of crack.
- c = half the length of an interior crack or length of a surface crack.
- ρ = the radius of curvature at the end of the major axis.
- σ = applied tensile stress normal to the crack.

When a crack start gowning, elastic energy is released. However, a certain amount of energy is gained as surface energy because of creation of new crack surface zone. The elastic strain energy released by the spreading of a crack in a thin plate is given by

- $U_E = \dfrac{\pi c^2 \sigma^2}{E}$

and the surface energy gained by the creation of the crack is

- $U_S = 4c\gamma$

According to Griffith, such a crack will grow and produce brittle fracture when an incremental increase in its length does not change the net energy of the system. This all explanation was for uniaxial tension system. But, it can be extended to the case of biaxial stress including tension as well as compression. In this case it is important to considered that cracks are randomly distributed and that fracture happens when the stress value reaches the value that lead cracks to grow.

Ductile fracture:

Ductile fracture generally shows less attention than brittle fracture, mainly because it is less dangerous in engineering applications of metallic design.
Ductile fracture happens in a metal after extensive of plastic deformation. It develops at lower stress rate than brittle fracture. When a stress is applied to the metal which is above its ultimate tensile strength, the metal will fracture Figure (1) shows ductile fracture of an aluminum specimen.

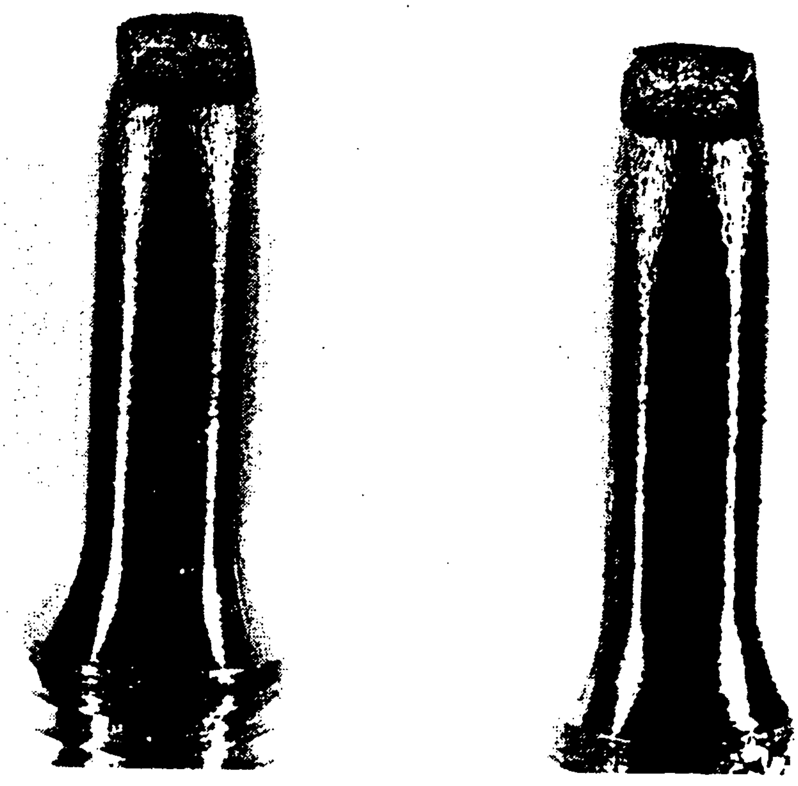
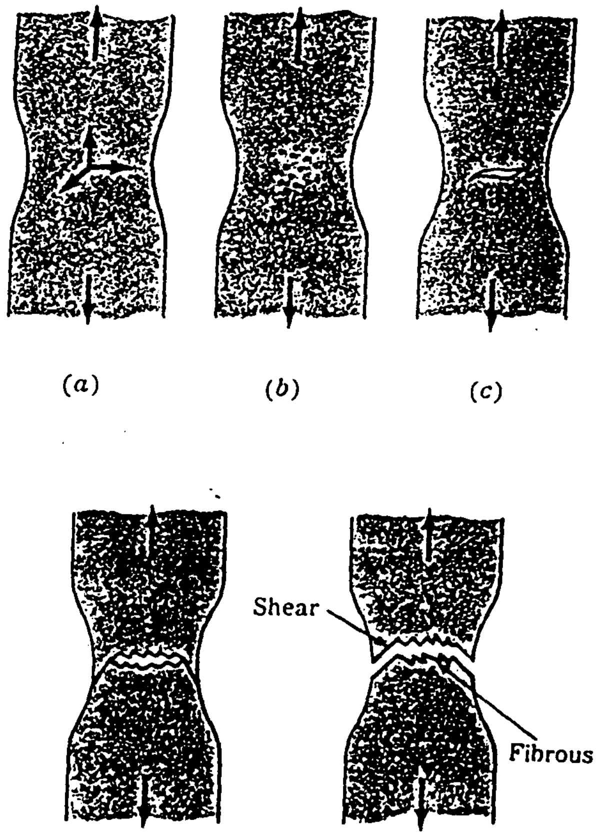


Figure (1)
Ductile fracture of an aluminum specimen

An important characteristic of ductile fracture is that a high amount of plastic deformation is needed for propagation of fracture crack; as a result, the process of plastic failure can be finished at any stage, provided that the operative stress is reduced to a value not more than flow stress of the material before crack.

Three steps can be observed in the ductile fracture process.

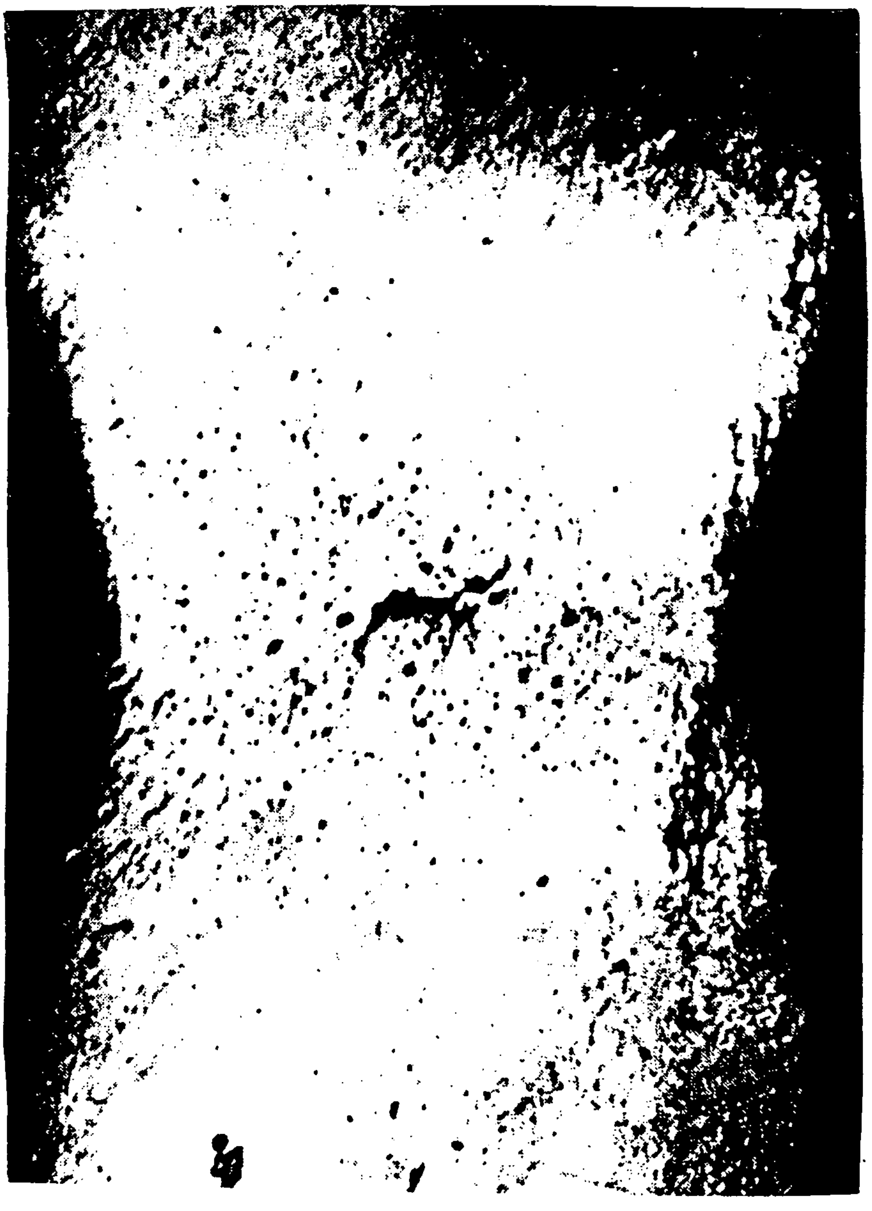
- The specimen creates a neck, and cavities form within the necked area as shown in Figure (2a, b).
- The cavities in the neck collect into a crack in the center of the specimen and grow toward the surface of the metal in a direction perpendicular to the applied stress (Figure 2c).
- When the crack reaches the surface, the direction of the crack changes to 45^o to the applied stress, and fracture results (Figure 2e).



(a) (b) (c) (d) (e)

Figure (2)
Steps of ductile fracture

Figure (3) shows an internal cracks in the necked area of a deformed metal of high-purity copper.



Figure(3)
Internal cracking in the necked area of a polycrystal metal of high-purity copper

Transition from ductile to brittle:

There are many factors causes to change type of fracture of a body center cubic (BCC) metal from ductile to brittle, which is achevied by decreasing the temperature, notching the metal, and increasing the strain rate. The impact test, which is described by Hayden et al (1983) can be used to find the temperature range over which the transition happen. In this case, the determination of the transition temperature depends on:

- The transition in energy absorbed.
- The transition in ductility.
- The change in fracture behavior.
- The contraction at the root of the notch.

Some materials such as steels, fracture in a ductile behavior rather than in a brittle behavior, they absorb more energy. Accorrding to this fact the impact test is usually used to calculate the temperature of transition from the ductile to brittle fracture which happen as the temperature of metal is lowered. The transition temperature is also dependent on the shap of the notch in the metal.

Figure (4) shows the relative effect of temperature on the impact energy of some types of materials.

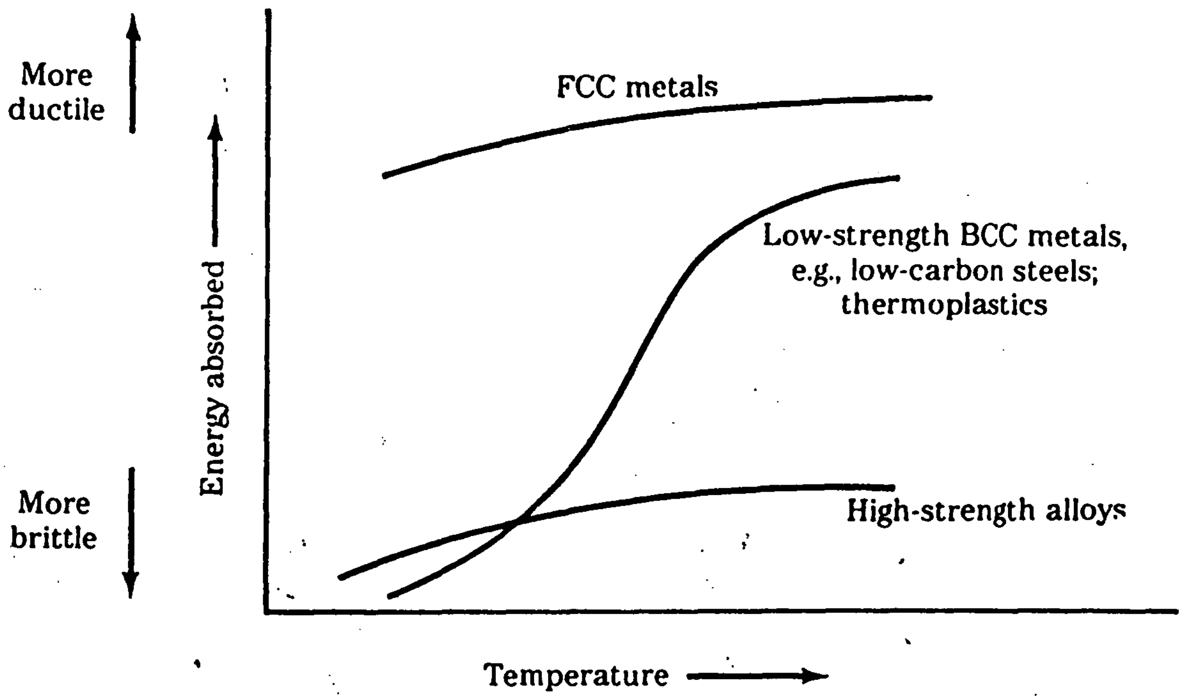


Figure (4)
Effect of temperature on the energy absorbed upon impact by different types of materials

Fracture Toughness:

The fracture of a specimen containing crack begain at a piont with highest stress concentration. The critical amount of stress-intensity factor which leads damage in the specimen is called fracture toughness. Let us consider for instance, a plate under uniaxial tension with an edge crack or a center-through crack as shown in the Figure (5). As indicating in the Figure (c), stress rate is highest at the tip of crack.

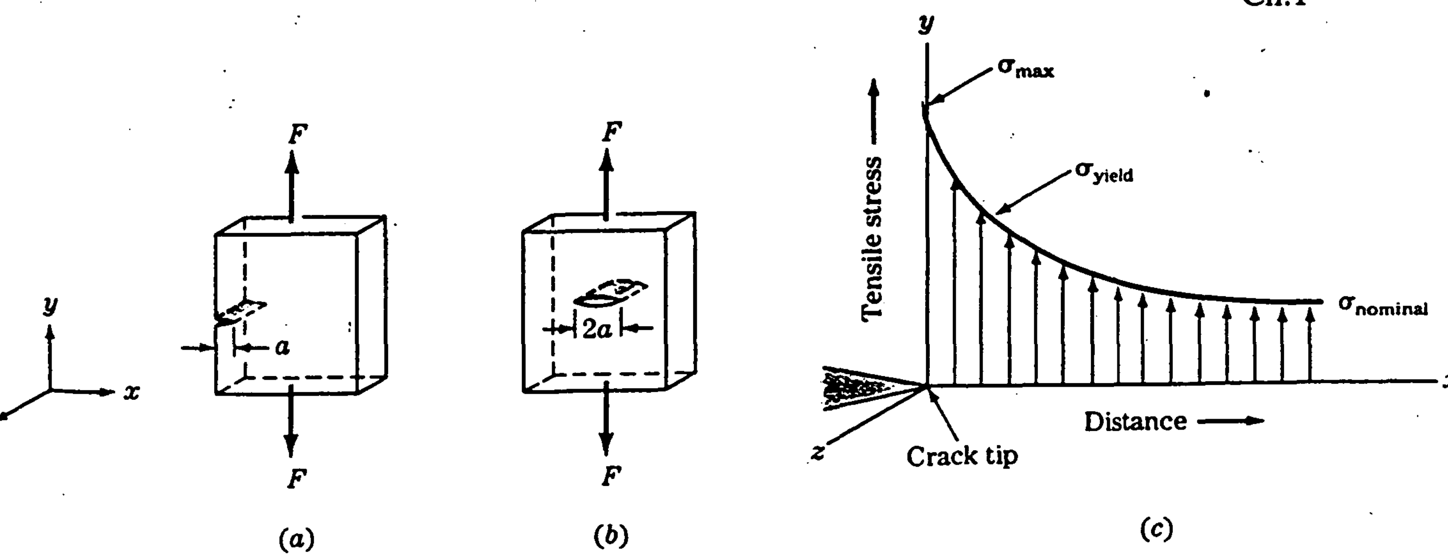


Figure (5)
Plate sample under uniaxial tension

From experimental work, it was found that the stress intensity at the crack tip depend on the applied stress and width of the crack. The following equation was drived:

$K_I = Y\,\sigma\,(\pi a)^{1/2}$

where

K_I	Stress intensity factor
σ	Applied stress
Y	dimensionless geometric constant usually equal to 1
a	edge crack length or half of an internal through crack

Stress concentration area is most suitable area to fracture occure; for example top of sharp crack. From Figure (5c), it shows relative of distance from sharp end to tensile stress.

Stress intensity at the crack tip is dependent on width of crack and applied stress.

The stress intensity which cause failure to occure in metals is called fracture-toughness Kci

Toughness and Impact Testing

Each material has a certain amount of energy which can be absorbed before fracturing. The measurment of this energy is called toughness. In engineering design toughness is consider one of the most important factors especially, when designing a material to withstand impact load without fracture is considered. The schematic diagram shown in the Figure (6), is the simplest appparatus used for impact-testing. A V shaped notch specimen is used in the impact-test, which is placed across parallel jaws of the testing machanism. A heavy pendulum, released from a certain height, strikes the specimen on its downward swing, causing the specimen to fracture.

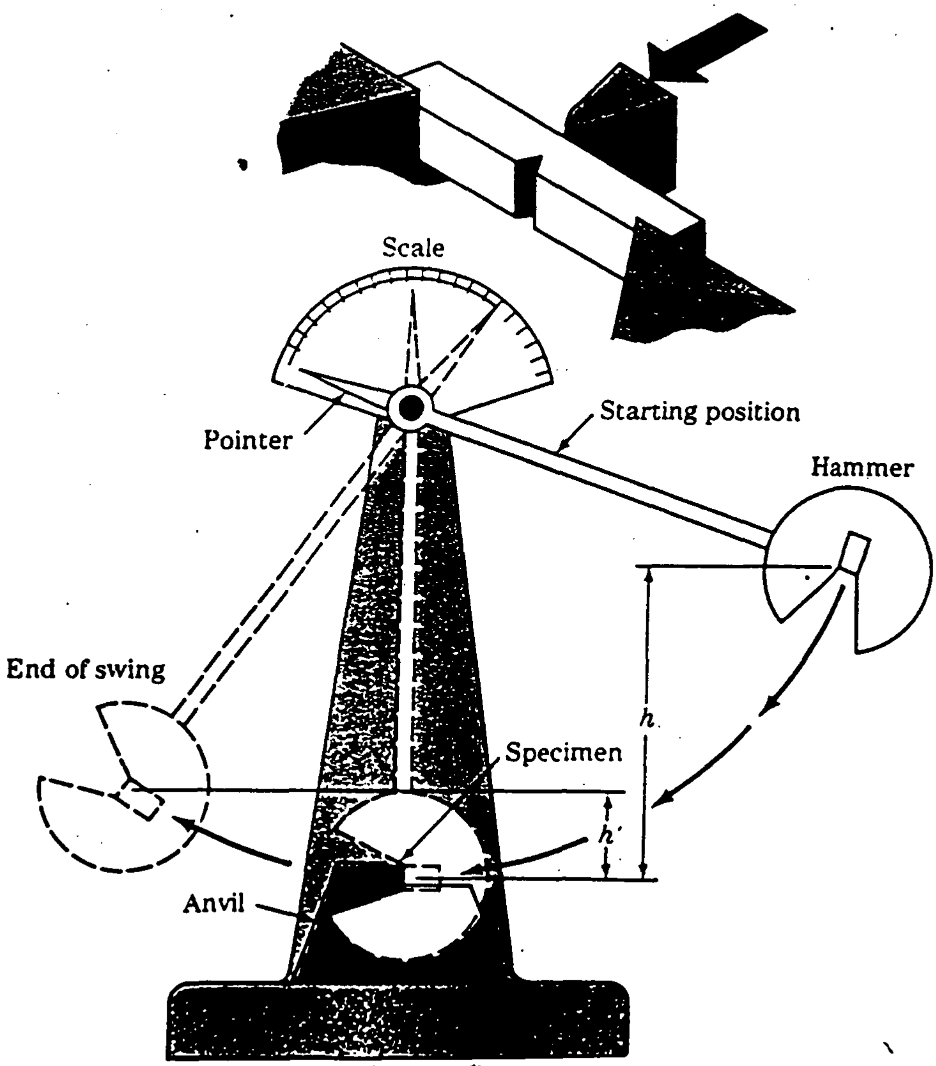


Figure (6)
Standard impact-test machine

From knowledge of the mass of pendulum and the difference between the initial and final heights, the energy absorbed in fracture can be determined.
In the presence of the notch the stress concentration at the notch produces fracture with small plastic flow. The impact test indicates the notch sensitivity of a metal resulting from the presence of internal stress raisers, such as internal cracks and grian boundary inclusions. furthermore impact test is useful as a production tool in comparing manufactured materials with other which have proved satisfactory in service.

To calculate the energy absorbed by specimen, the mass of pendulum and difference between the initial and final heights is required.

Figure (4) can be used to determine the temperature of metals. Metals may be made more brittle by reducing the temperture.

Fatigue Damage

Introduction

In a modern engineering design in which the safety factors is being continually reduced and the speed of operation of machine parts are continually increased. Therefore the studing of degree of dynamic loading to be withstand by these parts is considerable.
The objective of this study is deal with factors affecting the fatigue of metals such as temperature, stress, speed and so on.

Definition of Fatigue:

Metal parts subjected to repetitive or cycle stresses can be broken at lower stress than normal a single statice stress. This behaviour known as a fatigue.The relation between repetitive stress (S) and a number of cycles (N) is shown in Figure (1). The number of cycles needed increases as the stress decreases.
Shafts, gears, rotating parts, connecting parts are common parts in the machines in which fatigue failure happen.

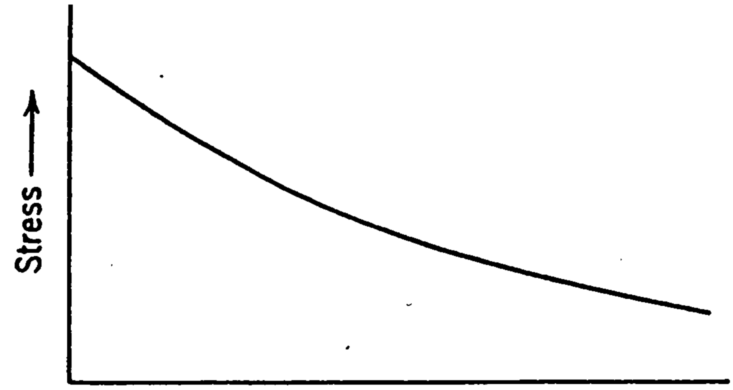


Figure (1)
Stress-No of cycles curve

Fatigue failure usually occurs at a point of stress concentration such as a corner, sharp ends or machine marks or at metallurgical inclusion.

Analysing of Fracture Mechanics in Fatigue:

There are two important stages in the fatigue process as follows:

- Fatigue crack initiation stage.
- Fatigue crack propagation stage.

For any given loading each stage consists of an appropriate number of cycles. Therefore total fatigue life (N_f) consists of fatigue crack initiation cycles (N_i) and crack propagation cycles (N_p).

$N_f = N_i + N_p$

The first stage includes microcrack nuceation, which will grow along crystallographic planes, or coalescence of two or more cracks until a crack appears and that will lead to build its own zone which can grow under nominal stress.

Many studies have been done on fatigue crack initiation for different structural materials. Thompson (1958), and Dowling (1977) cited by Bily (1993) are indicated that microcracks in low-cycle area will start to be created in the early stage of the fatigue process.

Initiation stage will play only a small role in the fatigue life, the total fatigue life will calculate by the number of cycles which is necessary to propagate the crack up to the end of fracrure.

Classification of the Fatigue Process :

Researchers have classified the fatigue process into three overlapping sections:

- Fatigue hardening/softening taking place as a result of interaction between structural defects in the whole loaded volume. In this stage the behaviour of the fatigue hardening/softening mainly depends on the initial state of the material and on the factors of cyclic loading like stress amplitude, mean stress, temperature and so on.

- Nucleation of fatigue cracks which results from the localization of cyclic plastic deformation at nucleation positions.

- Propagation of fatigue cracks. This step may be ruled by cyclic plastic deformation localised in the plastic area.

The fatigue process can be represented by the following Figure (2).

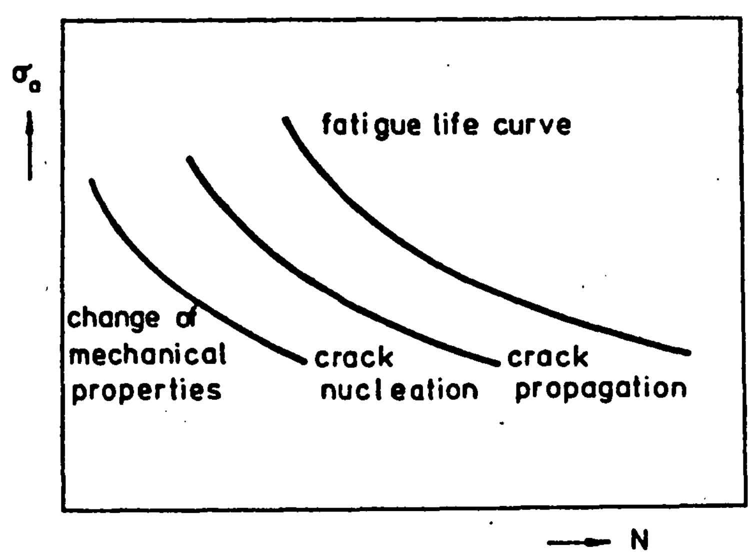


Figure (2)
Steps of Fatigue process

The fatigue life curve represents the end of the crack propagation stage and therefore simultaneously the end of the interior fatigue process. The curve 2, 3 (crack propagation, crack nucleation), show the end of the hardening/softening step and the end of the nucleation stage. It should be notched that there is no clearly defined border between the special stages. For instance nucleation of micro-cracks occurs even during the hardening and softening change, and therefore micro-crack size describing the border between two stages is only a matter of convention.

The state of the special curve in the Figure (2) strongly depends on service, metallurgical and technological factors.

Two kind of surface area can be recognised during fatigue failure.

1) Smooth surface area, which occure due to the rubbing of the two faces of crack across the section.

2) Rough surface area, which occurs due to high load for the remaning cross section area. Figure(3) shows light fracture graph of fatigue fracture surface of a keyed shaft of 1040 steel.

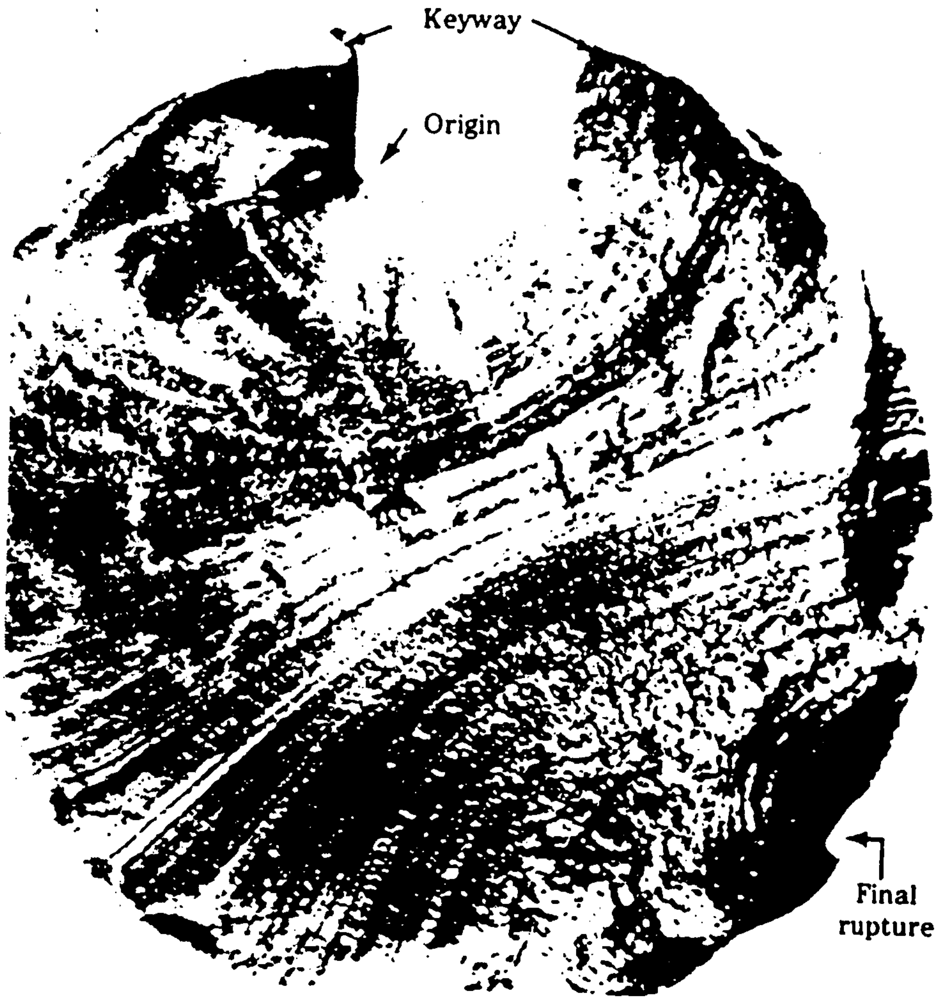


Figure (3)
Fatigue surface of a keyed shaft 1040 steel

Nucleus are appear on the fracture surface, mostly at the edge of the fracture where the crack create. This nucleus are in general brittle and smooth when the two fracture surfaces start to rubbing together. In additional the area around this spot is smooth also, which is indicating the crack propagation line. After a certain cycles of load a remaining metal can not withstand with the effect of load and stress concentration and damage will occur. Figure (4) shows diagrammatically the steps in which the damage is developed.

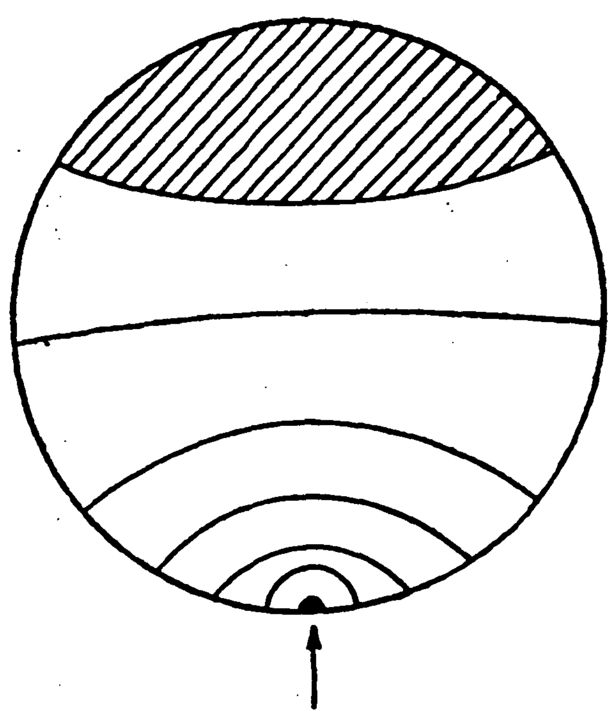


Figure (4)
Fatigue crack propagation under repeated load

Two types of fatigue behaviour is recognized in metals:

1) Fatigue limit definite: which occurs in iron and mild steel. The curve in Figure (5) shows this behaviour, at the stress (So) and the value of (N) which is usually 10^5 and 10^7, the curve becomes horizontal, and as stress less than So fatigue will not occurs. The same behaviour has also been found to occur with some strain ageing aluminium alloys.

2) No fatigue limit definite: Most metals presents this behaviour, which is shown in Figure (5). S/N curve falls continuously.

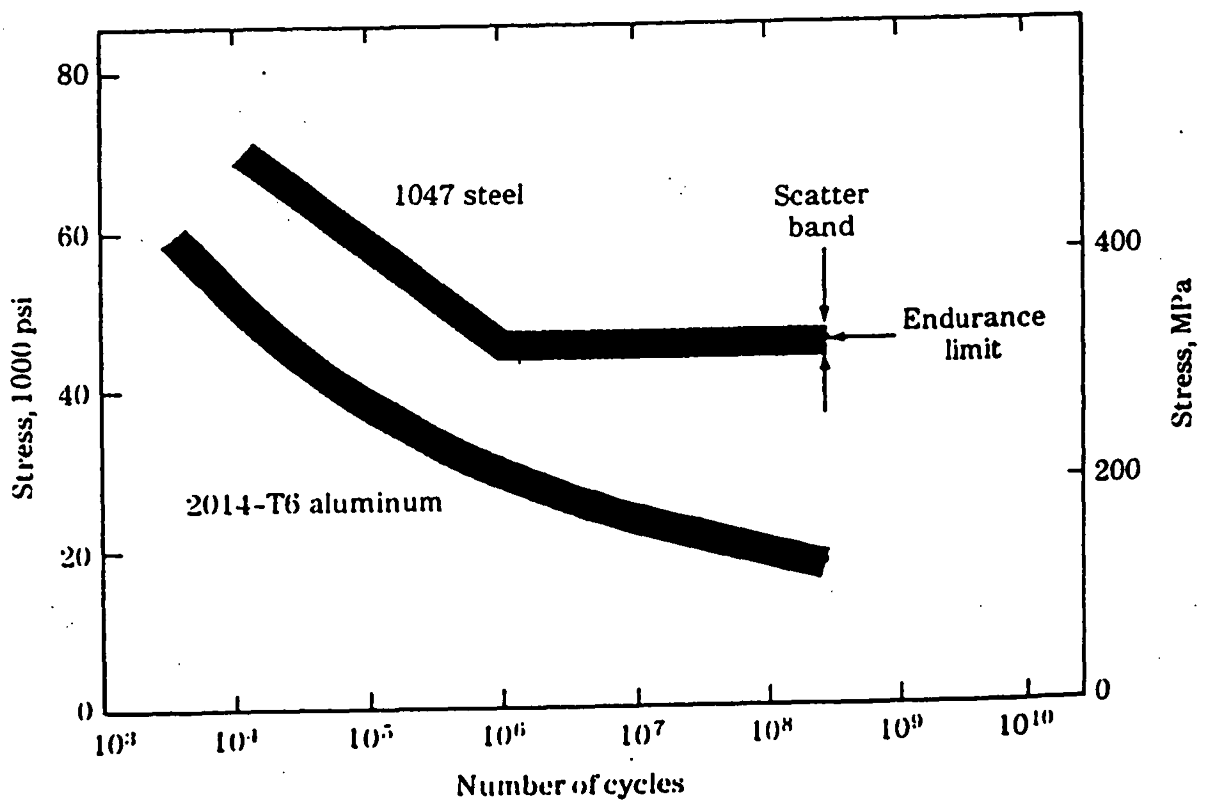


Figure (5)
Stress/number of cycles curve for Steel and Aluminum

The fatigue damage

The most important problem which worries designers is that in ductile metals damage will occurs without any sign of plastic deformation when these metals are subjected to repeat stress.

The following structural changes happen during the fatigue steps:

- Initiation of crack. It is the first step which occurs in the fatigue failure process which is due to plastic deformation in the structure of metals.

- Slipband extrusions. Due to plastic deformation is not a totally reversible system, so that any changing in the direction of plastic deformation will cause surface ridges and grooves named slipband extrusions. Any surface damage along slipbands leads to create cracks at or near the surface which grow into the specimen along the planes subject to cyclic shear stresses. This step of fatigue process is called stage I, and the rate of the crack growth is very low.

- Crack propagation. Crack during stage I will grow in a ploycrystalline metal only a few grain diameters before it changes its direction to be perpendicular to the direction of the load. In this case, rapid rate of crack growth is well-defined in the stage II of fatigue process, and the fatigue striations will start as the crack advances across the cross section of the specimen. Usually these striations are important to determine the origin and the direction of fatigue crack growth.

- Ductile fracture. When the cracks reach the certain zone so that the remaining specimen at the cross section cannot withstand the applied load, ductile failure will occur.

The idea that fatigue failure occurs without any previous plastic deformation means that the degree of stress concentration is not too high in this area. This is because of either fault in design or imperfections in metal, which can be liquidated by plastic deformation. For instance Pope (1959) drived an equation for stress calculation around an elliptical hole which is shown in figur(6)

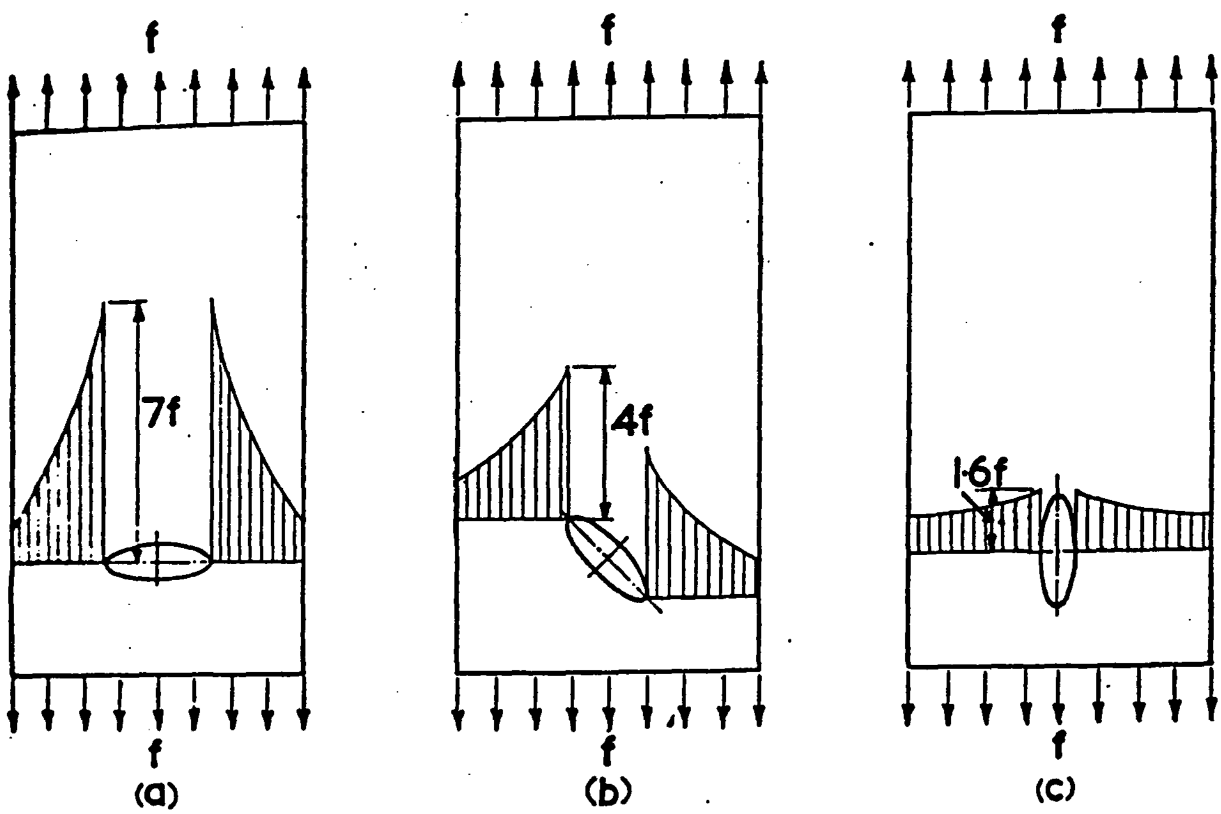


Figure (6)
Tensile test specimen with elliptical hole

The equation is:

- $F_{max} = F (1 + 2a/b)$

Where
- a = major axis of the ellipse
- b = minor axis of the ellipse
- F = mean stress
- F_{max} = maxiumum stress at the edge of hole

It is necessary to take into consideration that any mark or any sort of scratch is considered as a stress raiser. In this regard any part of a machine should be carefully machined and have a very fine smooth surface in order to prevent stress rasier.

Dislocation Theory and fatigue

To more clear of understanding of fatigue theory is, that fatigue cracks are started by slip. The strongest evidence for this fact is that, transcrystalline fatigue damage begins with cracks that create in or parallel to slip bands. It was clear that, at high temperatures the grian bounderies slide easily, and fatigue damage begins there. The fatigue damage is not because of developing a large internal stress. But, it is clear by the fact that, fatigue damage happens at stresses well below the static breaking stress and by the observation that cracks begin on those slip bands on which there is the biggest range of stress, not those on which there is the highest peak stress. There are three ways in which slip might be occurs to produce a notch.

- First way as clear in the Figure (7), in which the sequence of intersecting slip movement occur. The source S_1 operates before S_2 on each cycle due to the resolved shear stress on its slip plane is supposed to be greater. If the cycles repeated the movements, the notch would get deeper. This way prefer a free surface to start.

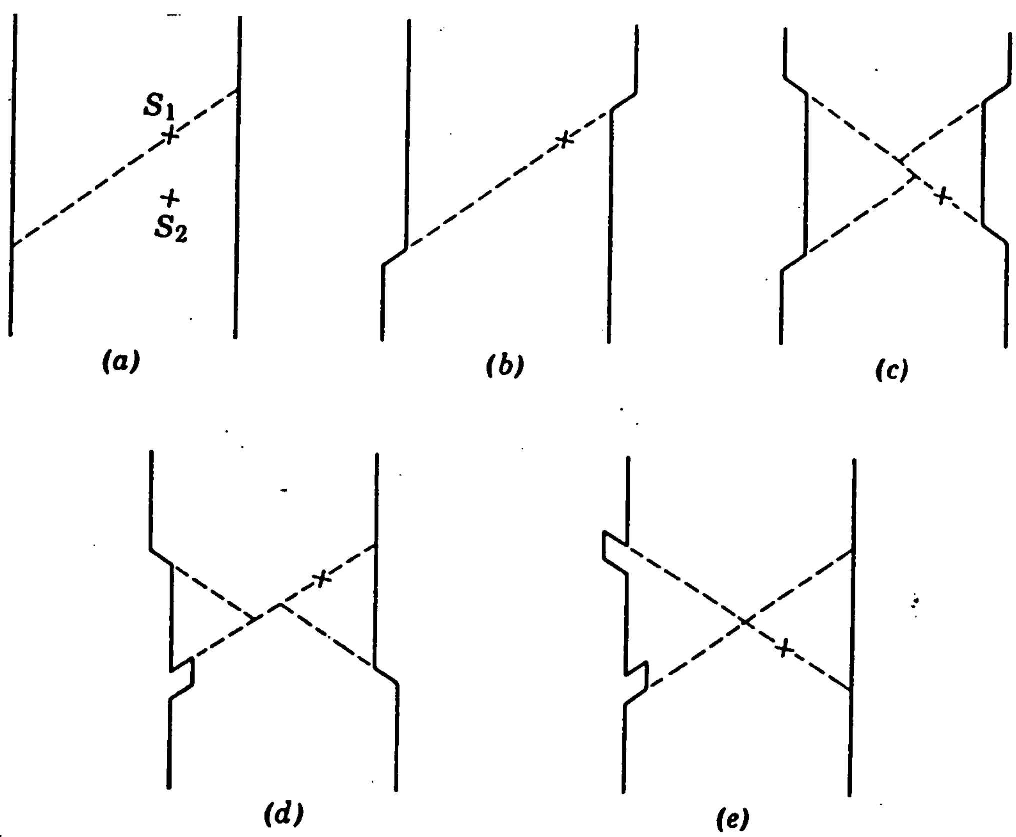


Figure (7)
Producing an intrusion and an extrusion by the sequence of slip movements

- Second way as clear in the Figure (8), in which that edge dislocations come opposite each other on nearby planes and combine to make the gavity ABCDA'B'C'D'. The edge dislocations having burgers vectors parallel to AD. A screw dislocation PQ with the same burgers vector moving round the cavity at its lower end P will then extrude the slab CDD' C'EFF'E'. This is the initial fatigue crack. The function of the initial cavity ABCDA'B'C'D' is to keep the screw dislocation moving in a fixed path under an alternating stress suitably inclined to DF. This is same as in first way, it prefer a free surface to start.

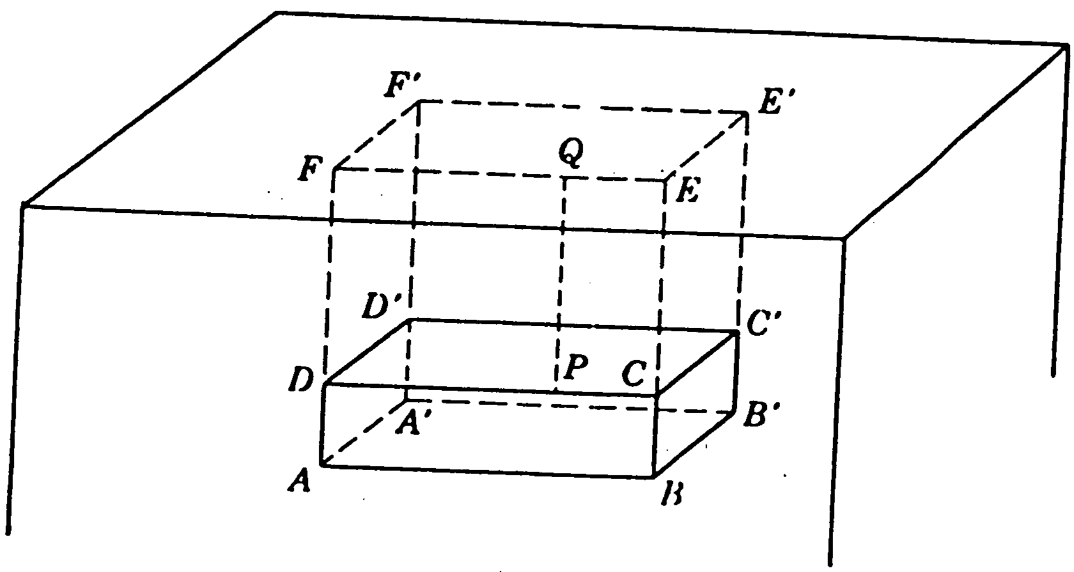


Figure (8)
Producing an extrusion

- Third way as clear in the Figure (9), a screw dislocation traverses the slip plane WXZ in the direction XW and creates a step in it at Y. Slip on the plane in the direction ZX then creates a cavity opening on the front face shown at ABCD. Such a cavity would only close up on reversing the stress if the slip movements exactly reversed. In this way it prefer the surface with atmospheric contamination which helps to keep the crack open.

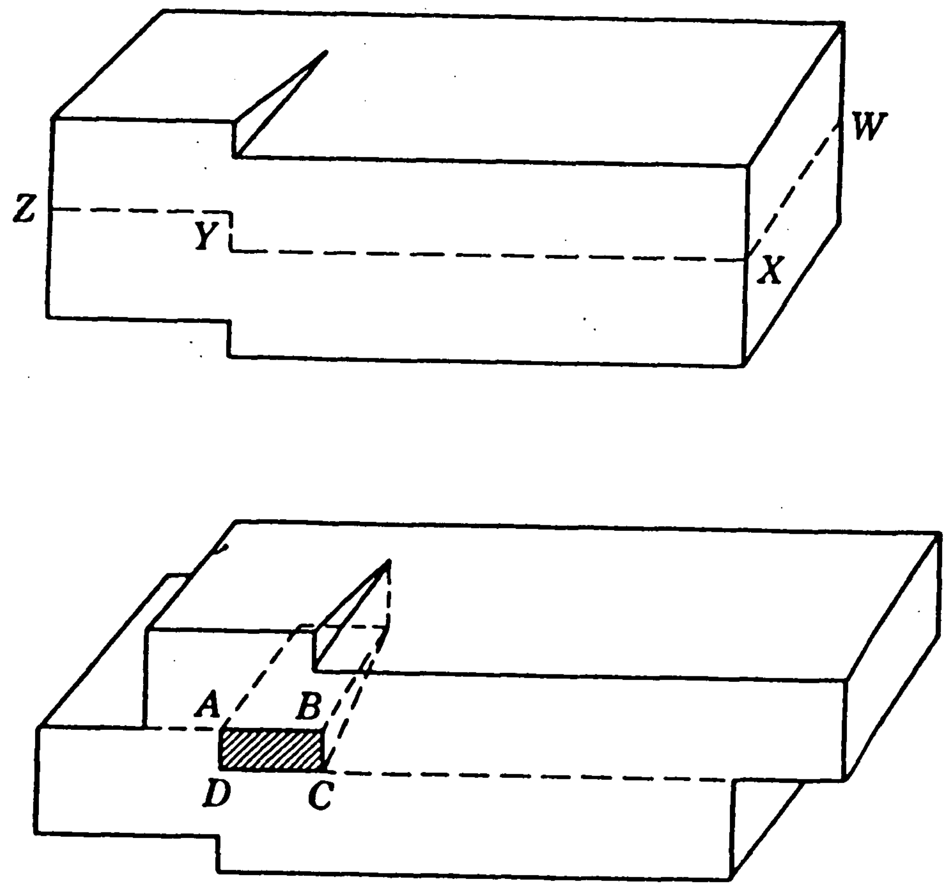


Figure (9)
Producing an intrusion

The mechanism of fatigue failure

There are two main phases in the mechanism of fatigue failure:
1) Crack initiation.
2) Crack propagation.

Metal physicists have given considerable attention to the processes ruling the initiation of the fatigue crack and have worked to understand the type of internal structure a metal must have to resist the initiation of fatigue.

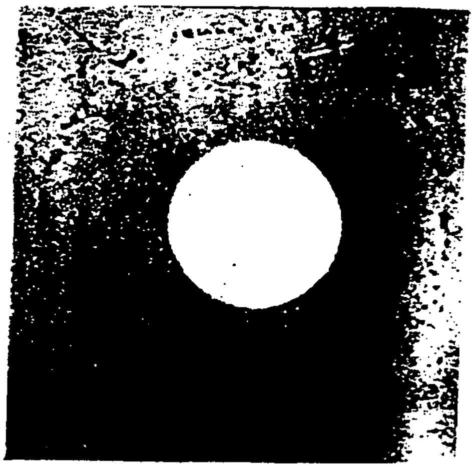
Gough (1923) studied the development of slip bands in the polished surface of a metal.The result of his stuey was.

- Below the elastic deformation limit of a metal, slip occurs at high stress points. In Gough's study the edge of grains is most likely to suffer high local stress.

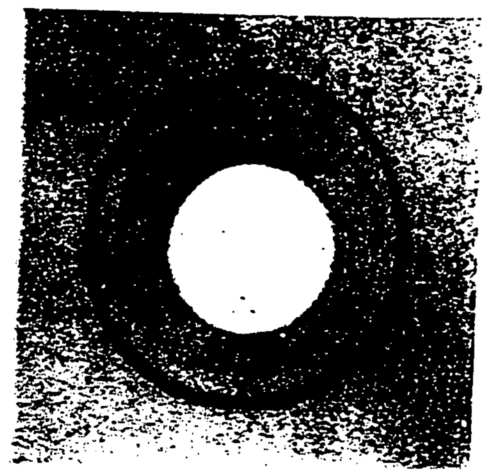
- When the metal is subjected to an oscillating stress the number of the slip bands will increase.

- When these groups of slip bands are formed the matel work-hardens locally, so when the stress is below a critical stress to cause fatigue, the groups of slip bands will occur and leads to spread through the crystals, and after a certain number of reversals the condition will become more stabilised, the separation of the slip band will stop and the failure will not occur. However, if the magnitude of the stress is above critical value, the slip bands will not be stabilised by work-hardening and the groups of slip bands will continue to spread through crystals, until the failure will occur.

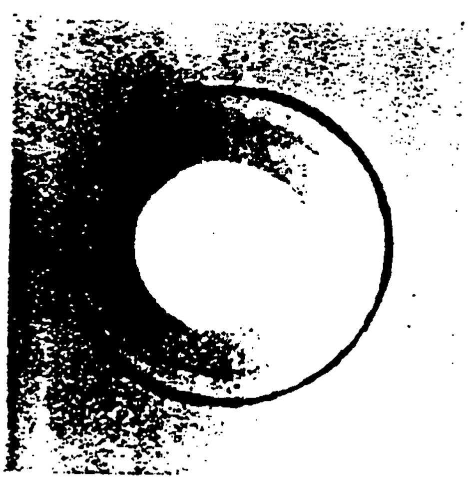
The study implemented by Gough and Wood (1939) used X-ray to examine the deformation and break-down of the crystal structure into crystallites under effect of static and cyclic stress, they found that the degree of crystal deformation which causing fatigue failure are identical see Figure (10).



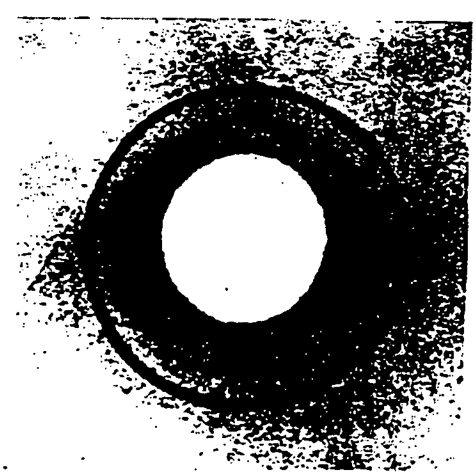
(a) Specimen 3A40
In normalized unstressed condition



(b) Specimen 6A24
After failure under static stress of 26·3 tons sq. in.



(c) Specimen 6A26
After $10{\cdot}518 \times 10^{6}$ cycles of stress range 26·7 to 13·3 tons sq. in. (unbroken).



(d) Specimen 7A28
After 12×10^{6} cycles of stress range 26 to 7 tons sq. in. (unbroken)

Figure (10)
Gough and Wood sudies, using X-ray to examine the break-down of a crystal structure

Orowan's Theory

Orowan's theory for analysising fatigue failure was, that the fatigue strength of material is a function of its local rupture strength, the magnitude of stress raiser and the elastic behaviour of a metal. Pope (1959) has simplyfied Orowan's theory,and explained as follows.

- Even in the pure metal there are number of small inclusion and crystal lattice defects at the boundary or a crystal itself, which will cause to raise stress in metal.

- Orowan plotted the relation between applied stress and number of reversals to fracture.Plotted on log scales the expression he derives gives a curve as shown in Figure (11)

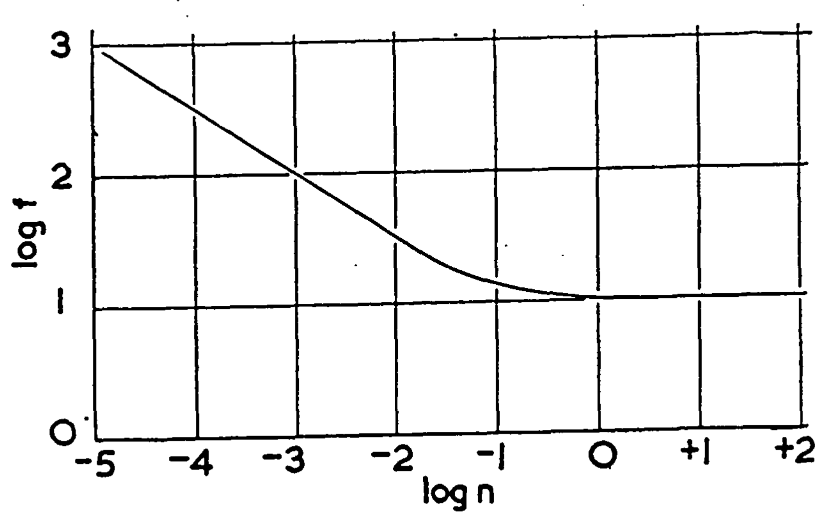


Figure (11)
Relation between applied stress and number of reversals to fracture

Plastic Deformation at Crack Tip

The cyclic plastic deformation at the crack tip during crack propagation is very important in the process of fatigue growth rate. Generally speaking, plastic deformation will happen more easily at higher temperatures. It follows then that plastic deformation would be more difficult at lower temperatures. Therefore the fatigue crack growth rate at higher temperatures could be recognised to be higher than the room temperature, and fatigue growth at lower temperatures visa versa.
In fact, this is often more complicated, since the interaction of the fatigue and brittle crack growth may may take place at the lower temperature, and it may play a role at high temperatures.

Fatigue Crack Growth

Introduction

There have been many studies of crack growth rate since 1960'S. Efforts have been made to investigate fatigue crack growth rate (Yan and Lei, 1994; Goel and Chand, 1994; and Eason et al, 1992; Edoutos and Zacharopoulos, 1987), and over the past two decades, many studies has been made on fatigue crack growth analysis.

Current fatigue crack growth procedure in the commercial and industrial manufacturing works is of particular interest to researchers of the field of mechanical engineering.

Since the 1960's much research has been devoted to reviewing crack growth in different materials due to their propagation occupatize on a large number of fatigue domains for most engineering materials and structure, however, there is an inadequate current understanding of fatigue crack analysis, particularly fatigue crack growth in aluminium alloys.

Fatigue crack growth behaviour has been evaluated with the assumption that crack-tip deformation may be ruled by fracture mechanisms factors such as stress intensity factors (K), strain energy release rate (G), J- integral, crack opening displacement (COD), and crack sliding displacement (CSD) for single mode loading conditions. The Dugdale-Bilby, Cottrell, Swinden (BCS) models used by most researchers were considered as the most largely used method for developing fatigue crack growth theories.

Fatigue crack growth under combined Load

Yagawa et al (1989) conducted research in order to evaluate stable and unstable crack growth behaviour under combined force of thermal shock and tension simulating. Two series of experiments are demonstrated:

- One to study the effect of material deterioration because of neutron irradiation on the fracture behaviour.

- And the other to study the effect of system compliance on fracture behaviour.

These experiments made it clear that the influence of deterioration of material characteristic on the behaviour of crack growth under the pressuralized thermal shock (PTS) is significant. In addition the influence of system compliance is indicated to be another important parameter on the stability of the fracture under PTS. Furthermore, the J-integral factor with thermal effect in the three-dimensional elastic-plastic field is successfully used in fracture analysis procedures related to PTS.

Current fatigue crack growth processes in the commercial nuclear power industry do not clearly specify how compressive loads are to be withstand, and therefore, regulatory agencies usually recommend a conservative approach requiring full consideration of the loads.

Study by Bloom (1994) demonstrated that a more realistic approach can be formulated using fatigue crack growth closure models. It has been used the recent series
of fatigue crack growth rate tests (Jones et al 1993) in order to provide additional validation of relevant crack closure models. Based on the comparisons between the various crack closure models and the more recent test results of Jones et al, it can be concluded that the Newman et al (1986) crack closure models can be used with confidence to account for negative R-ratio effects in pressure vessel steels.

Fatigue Crack Growth Experiments

Connally and Brown (1993) conducted a study to asses the mechanism of crack growth using micro-mechanical fatigue testing. In this research, fracture and fatigue of silicon based micro mechanical devices were investigated. The fatigue crack growth was measured by detecting the shift in the natural frequency leaded by the extension of a pre-existing crack introduced near the fixed end of specimen (cantilever). They found that the crack growth rate does not accelerate with increasing crack length, which shows that the crack growth rate is not dependent on the magnitude of the stress intensity.

Goel and Chand (1994), performed crack growth rate experiments using an intermediate single overload cycle in constant amplitude load tests. For a particular overload ratio, three to four tests are performed by using the overload cycle at different crack lengths.
The test results shows behaviour generally consistent with the wheeler model in that retardation happen within the overload generated plastic area. As is typical for such tests the retardation increase with increased overload ratio. And also they found that the crack growth rate decrease in the first 12% of the retardation area and then return to the normal rate toward the end of the retardation area. Finally the principal result of the study was to develop of a functional form for the crack growth rate within the retardation area which is function of the overload ratios.

Chand (1992) performed crack growth experiments on the crack closure and propagation to determine the effects of simple load interaction. The experiment was performed on centrally notched specimens of aluminium alloy under single overload and block loading conditions. With comparing the behaviour of crack growth rate (FCGR) with those found experimentally, It was found that the predicted FCGR often agrees with the trend of experimental FCGR behaviour and supplements either exact or conservative estimates of the FCGR.

Behaviour of Crack under Tension and Compression Load

Under tension, cracks act as a stress raiser. Since the stress can not flow through the crack, it must flow around it, which causes an increase in stress concentrations at the end of the crack Figure (1a). Under the compression process, a closed crack will be able to transmit stress and therefore will not cause a rise in stress Figure (1b). This is why fatigue strength in compression is much higher than the tension process. This advantage of improving the fatigue strength by shot peening, surface rolling, nitriding, etc improves the fatigue qualities of rolled screw threads over machine-cut threads.

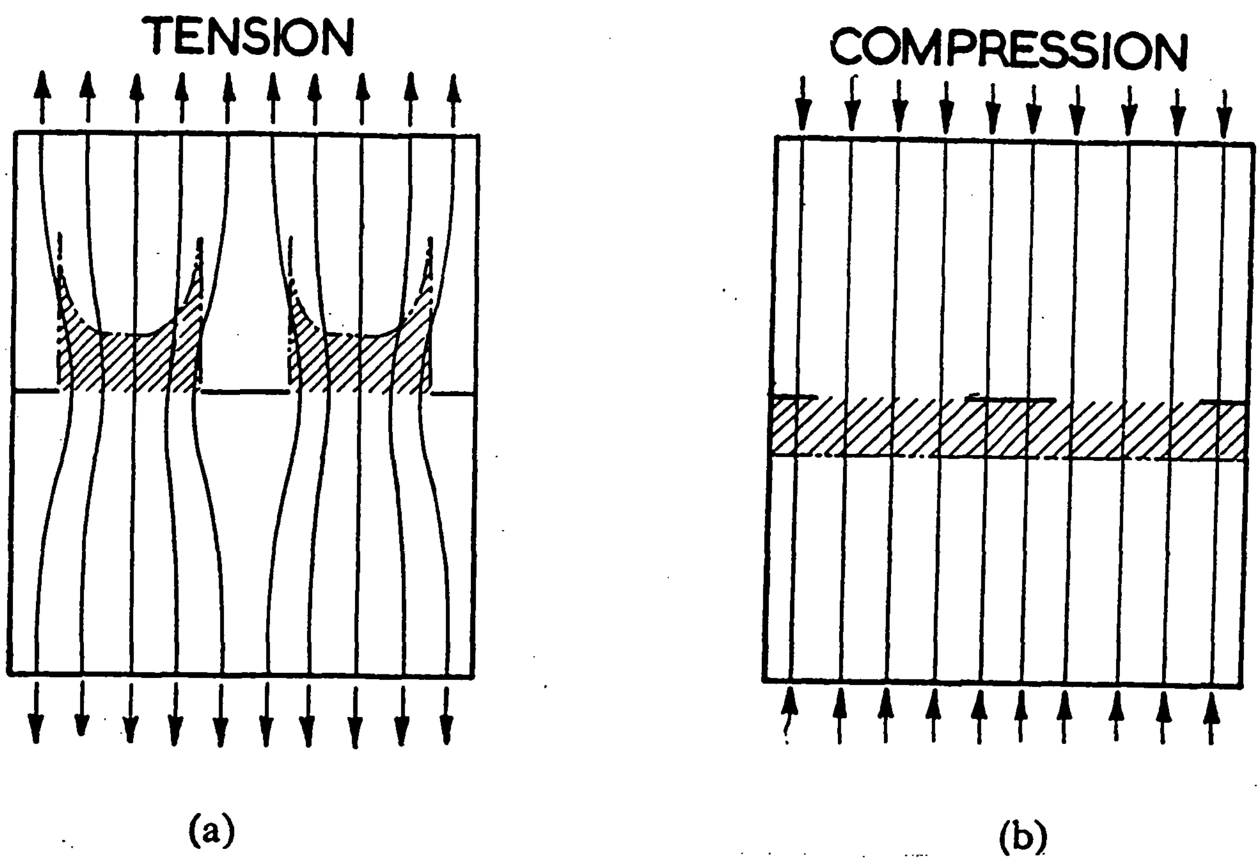


Figure (1)
Fatigue (1a) tension process, Figure (1b) compression process

Load and Fatigue Crack Growth

The rate of fatigue crack growth can be significantly affected by the magnitude and sequence of the loads applied under variable-amplitude loading conditions.

The prediction of service lifetime and the selection of alloys for maximum fatigue crack growth resistance are made complicated by the effect of prior loading on the rate of crack growth.

Study by Mcevily and Minakawa (1988) presents a review of the lifetime on load-interaction effects on the fatigue growth.

There is evidence to suggest that the retardation effect associated with a tensile overload occurs because of increased crack closure and a consequent reduction in stress intensity as proposed by Elber (1971; cited by Mcevily and Minakawa 1988).

The concept of closure was originally proposed by Elber, who attributed this phenomenon to residual plastic deformation in the wake of the crack. However, the extent of residual plastic deformation in the wake of the crack differs in plane stress as compared with plane strains.

Laird's Model

There are many fatigue crack growth models in the literature, but the model proposed by Laird (1967) and modified and specified by other researchers (eg Krasovskii et al 1979, and Krasovskii 1980). The Laird model of crack propagation is schematically presented in the Figure (2).

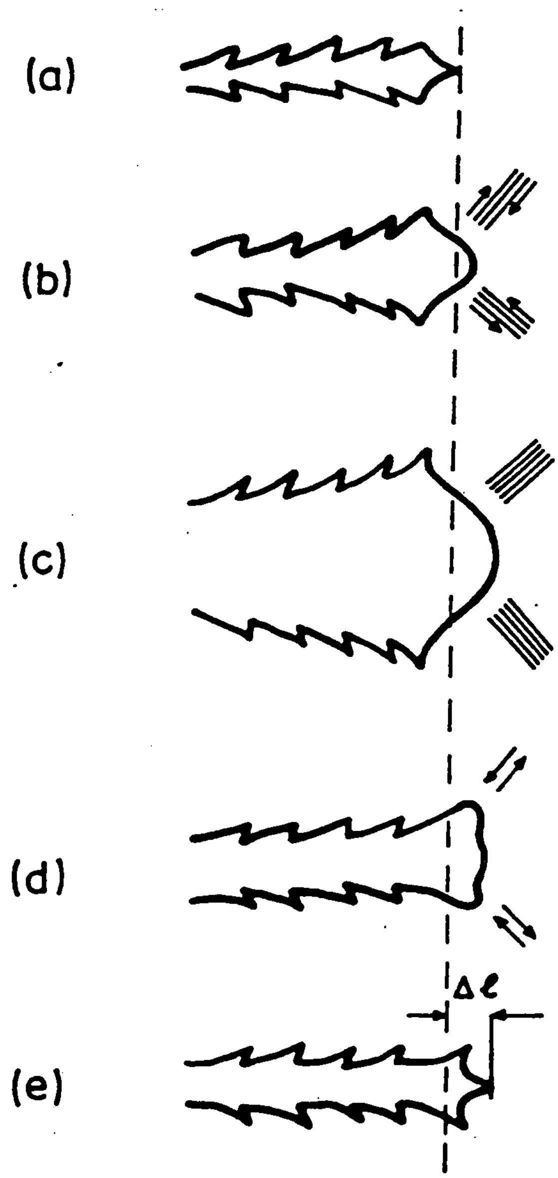


Figure (2)
Laird's Model for crack propagation

- State (a) represents the unloaded state of a body containing a crack.
- State (b) shows a plastic deformation which occur ahead of the crack tip due to the stress concentrating, which naturally occurs mainly in the slip planes inclined at 45 degree to the stress axis.
- State (c) shows that the crack front has shifted.
- State (d) in the direction of slip zones, "ears" that remain would be presented on the fracture surface as striations.
- Finally state (e) shows the loading cycle is terminated. This position is similar to the initial state of crack propagation, but the crack is longer by ΔL.

This mechanism results in the deformation of striations. The striations can not always been seen on the fatigue fracture surface. Possible reasons why this is so are:

- Firstly, the striations may be so weak that they are not observed. For instance, in aluminium alloys cycled in air, the striation are very marked as opposed to cycling in the vacuum where the striations are almost unobservable (Peloux 1969 cited by Bily 1993). However, the crack growth mechanism may be considered to be fundamentally identical in both examples.

- Secondly the Laird's model described here and modification show the most usual model but not the only one.

Fatigue fracture in many technical metals is a mixture of trans-crystalline and inter-crystalline fracture. Inter-crystalline fracture cannot be consider as a special case of Laird's model, because of the fact that plastic deformation in the slip areas of the crack tip is an inherent section of this model. A corrosive environment is required in order for the condition of inter-crystalline fracture to take place, but even a soft corrosive environment like atmospheric air is usually quiet sufficient for this purpose.

Areas of both purely trans-crystalline fracture and of mixed trans-crystalline and inter-crystalline fracture can be observed on the fracture surfaces. The fraction area of the inter-crystalline has a very good agreement with the stress intensity factors. The number of inter-crystalline facets increase with increasing stress intensity factor, reaches a maximum and then decrease again. Inter-crystalline facets at the maximum are fairly accurately developed, and the separation between them along the grain boundaries is easily observable.

Several inter-crystalline fatigue crack propagation models have been proposed, such as fatigue crack growth in low-carbon steels (Beevers 1980), in martensite steel (Richards and Lindley 1972), and in austenitic steel (Speckhardt 1976; cited by Bily 1993)

Fatigue Crack Growth and Plastic Energy Damage Theory

Wang and Thomas Hsu (1994) approached fatigue crack growth rate of metal using plastic energy damage accumulation theory. They recorded the following results.

- Crack growth rate is not a function of ΔK, but it is a function of average yielding strength, fracture toughness and the amplitude of stress intensity factor in areas II and III.
- Fatigue crack growth rate (FGGR) near threshold is found to be evaluated by maximum value of stress intensity factor instead of its amplitude.

- The onset instability value of ΔK is a specimen geometrical dependent parameter.

- The average yielding local strength has a significant effect on the threshold value K_{th}.

Paris (1962) cited by Wang and Thomas Hsu (1994) derived the first fatigue crack growth rate equation. The equation was based on fracture mechanics. This equation, known as the Pairs power law, indicates that the fatigue crack growth rate is proportional to the mth power of ΔK.

$$da/dn = c\ (\Delta k)^m$$

c and m = material constants.

Δk = stress intensity amplitude.

For many metals (m) is roughly equal to 4. Therefore, this equation is called Pairs fourth power law.

In order to understanding the behaviour of fatigue crack propagation, da/dn-k curve, which is shown in Figure (3), is divided into three different kinds of fatigue crack propagation rate.

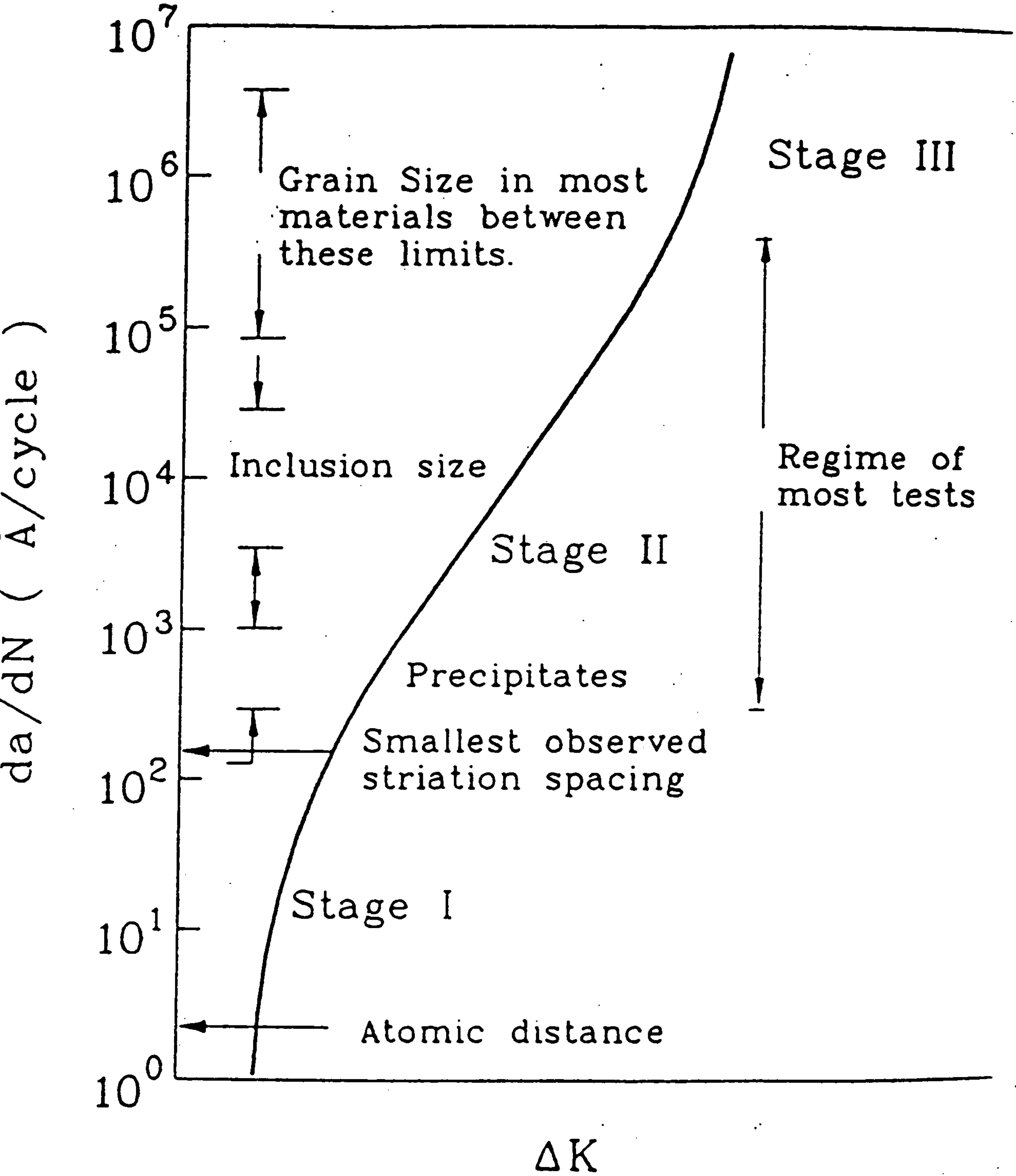


Figure (3)
Fatigue crack growth rate behaviour

- Stage I: In this stage the early development of fatigue crack is shown.The propagation rate is highly affected by the micro-structural of the metals for instance, grain size and the crush strength of grain.

- Stage II. In this stage, the length of the plastic zone ahead of crack tip is long comparing to the mean grain size, but smaller than the crack length.

- Stage III. In this stage the level of stress is very great, so that it causes a large plastic zone close to the crack tip as compared with the specimen geometrically.

Fatigue crack initiation occurs at the certain area, such as the notch-root. On the other side, crack propagation is the phenomena of the dynamic and successive failure, for example crack tip propagation grow zigzag by effects of cyclic stress.

For this purpose Shimada and Furuya (1987) believes that crack initiation and crack propagation processes should not bettered identically.

Shimada and Furuya (1987) investigated local crack-tip strain behaviours for crack initiation and crack propagating. The existence of the unified local strain field which help to combined the two fatigue processes by using the fine-grid-method. They reached the following results:

- Fatigue crack initiation was controlled by local-strain damage accumulation. For a quantitative expression of accumulative fatigue damage, was shown local strain damage accumulative curve ($\Delta\hat{E}_i$ versus Nc relation, Manson-Coffin curve), and linear accumulative damage law was based on ΔE value.

- Fatigue crack propagation rate (da/dn) can be successfully expressed by the proposed parameter, " local tip strain range " in the wide range from small to large fatigue crack. This is thought to show that fatigue crack propagation is really controlled by the local deformation very near to the fatigue crack tip.

Tokaji et al (1987) investigated the characteristics of fatigue crack propagation in a low carbon steel and in a high tensile strength steel in order to evaluate the effect of sheet
thickness. Crack propagation data are used over a wide range of growth rates, from 10^{-8} to 10^{-3} mm/cycle, for load ratios of 0.05 and 0.7 at room temperature in laboratory air. They concluded that "Near-threshold fatigue crack propagation is found to show a marked sensitivity to sheet thickness, and near-threshold growth rates decrease and threshold values increase with increasing sheet thickness".

Crack Growth Modes

loading Modes

There are three types of loading which cause cracks to appear in metals:

1) **Opening mode of loading:**

In this type displacement in the crack surface will be perpendicular to the plane of crack as shown in Figure (1a).

Stress intensity can be written by KI which indicate to the mode I.

2) **The shear mode of loading:**

This type leads two crack surfaces to slip on one another as shown in Figure (1b).

Stress intensity can be written by KII which indicate to the mode II.

3) **Tearing mode:**

This is caused by out-of-plane shear loading. The displacement of the crack surface will be within the plane of the crack and parallel to leading edge of the crack as shown in Figure (1c).

Stress intensity will be KIII, indicating mode III.

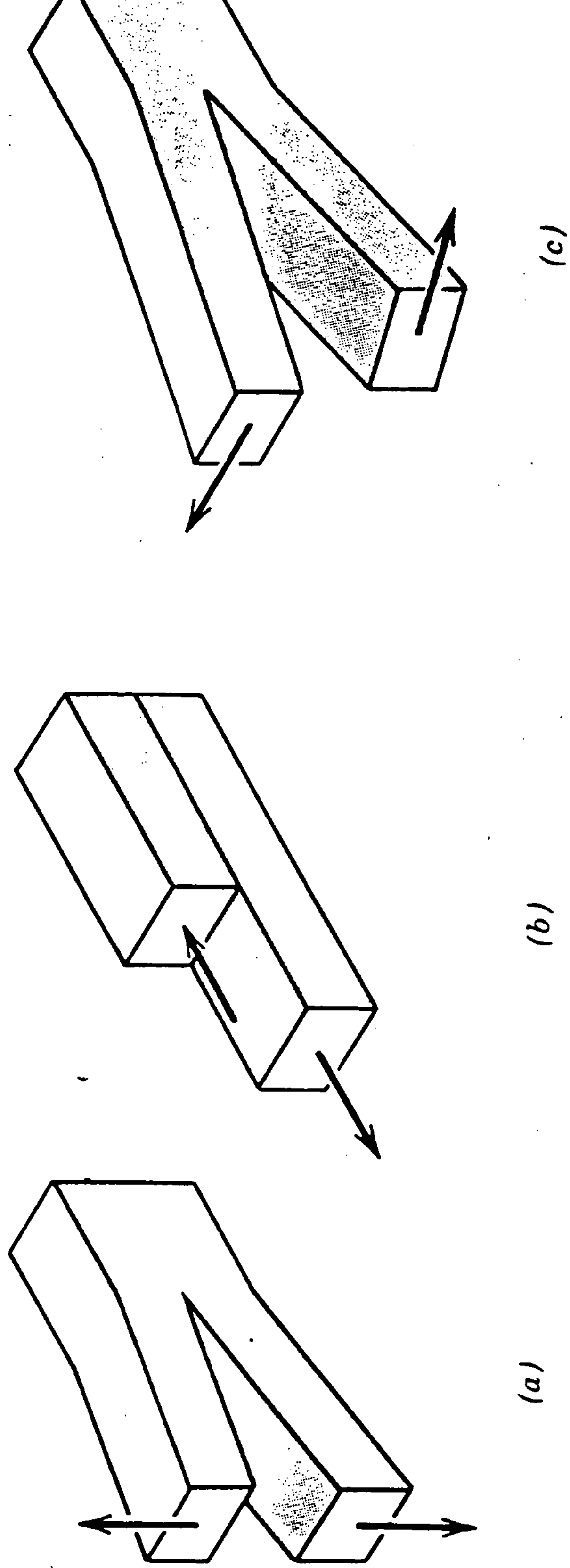


Figure (1)
Types of Modes

Explanation of modes crack growth:

Many metals in engineering applications experience stresses that are muti-axial in nature.The importance of mode II and mode III crack growth needs more explanation of the mechanism of crack nucleating and growth under these conditions. Figure (2) shows the cylindrical specimen subjected to multi loading. Mode I, mode II and mode III are components of stress or strain intensity which exist along the semi-elliptical crack front. The crack growth direction is on the maximum shear strain plane (γ_{max} and ε_{max} denoted the maximum shear strain and normal strain value on the crack plane, respectively). The surface crack length is denoted as 2c. From the Figure it is clear that the mode II component leads to extend the cracks length along the surface while the mode III component leads the crack to penetrate into the depth of the metal. In the case of cyclic or steady (tensile) normal strain on the crack plane effect the mode II and mode III crack growth rates significantly as it provides a mode I model separation of the crack surface, leading to the sliding displacements, which are associated with modes II and III to happen with less rubbing.

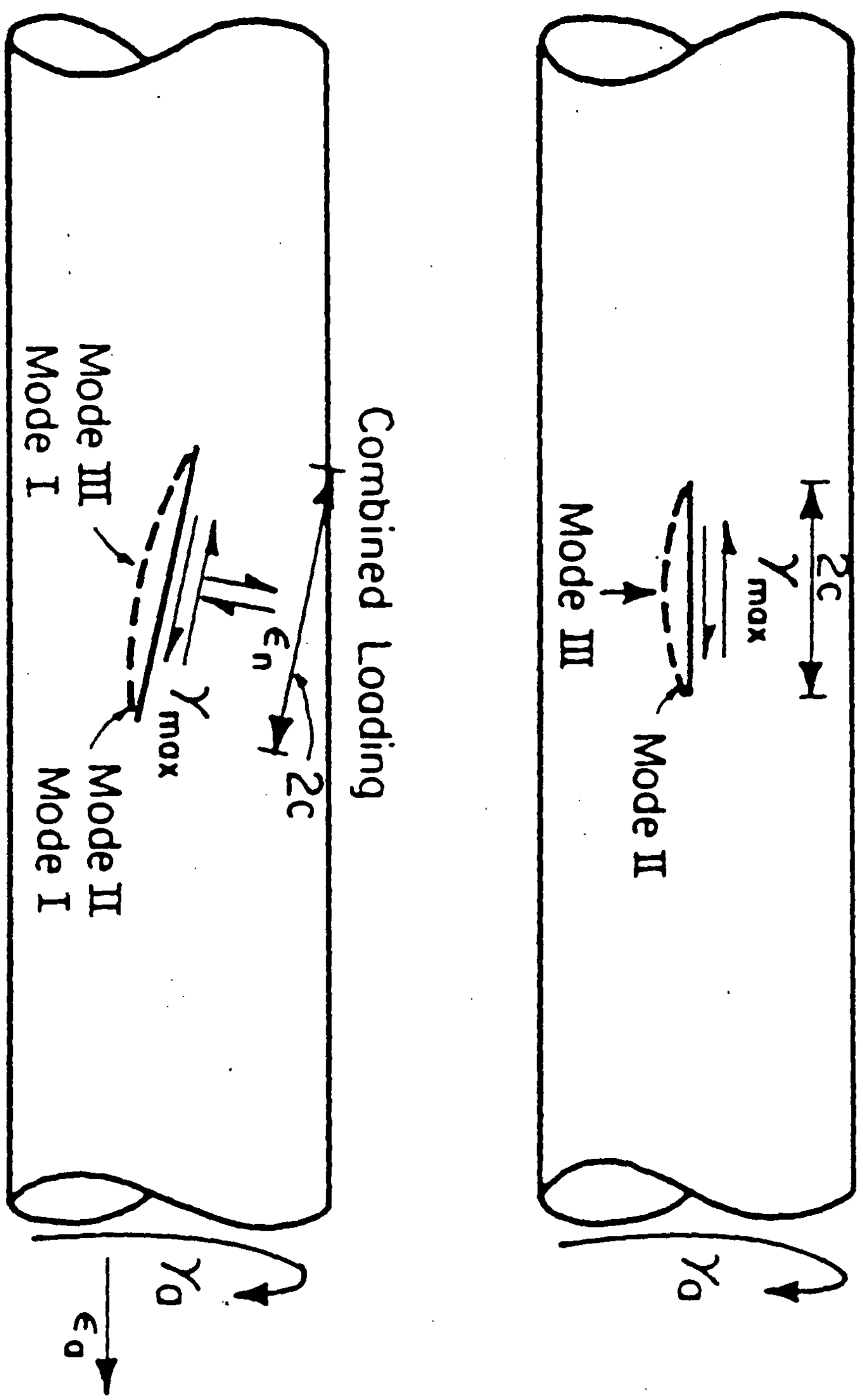


Figure (2)
Shear strain values on the crack plane for pure torsional and combined loading, and crack growth modes

Many investigations on torsional crack growth were made. Mode III crack growth is created by a circumferentially notched round bar subjected to pure torsion.

Hurd and Irving (1982) reached that mode III crack growth rates were 10 to 50 folds slower than mode I crack growth rate for the same stress intensity range.

Richie et al (1982) observed that rubbing and abrasion of crack surface under crack sliding leads to lower growth rates.

Tschegg et al (1983) have supported this effect. Other investigations studied a slant crack subjected to tensile loading experiencing both mode I and II components. In this condition fatigue cracks start to propagate under pure mode I (Kibler and Roberts 1970).

Pook (1979) reached that if mode I crack formation readily happen at the tip of main crack, then the ensuring behaviour is controlled by mode I displacements.

Smith (1980) found that in the case of a compressive strain component on the crack plane, mode II crack growth is still operative and leads to crack advance.

Mixed-Mode Crack Growth

In the past three decades, significant progress has been made in predicating the response of structures containing cracks under mixed-mode loading conditions and a large number of failure criteria have been suggested for this aim. Among these, maximum circumferential stress and the minimum strain-energy-density criterion obtained remarkable popularity. To make sure from the certain of failure criteria, a large number of researchers have been presented in the literature based on comparison of experimental data with analytical results.

Nayeb-Hashemi (1987) studied the failure modes of specimens containing surface-flaws under cyclic torsion. Three modes of failure such as three surface-crack orientations, subject to near-yield cyclic torsion, were evaluated.

The research showed that mode III failure was general to all tests because of the reduction in net cross section by mode III crack growth. Furthermore, it was found that the cycles to crack initiation and final fracture were two or three times more for flaws at 45 degree to the axis of the specimen. Moreover, it was concluded that the mechanism of crack growth is generated by linkage of elongated cavities.

Gdoutos and Zacharopoulos (1987) analysed theoretical and experimental study of crack growth in a plate subjected to unsymmetrical three-points bending, in order to study the mixed-mode crack growth system.

The specimens with razor-made cracks placed at different distances from the mid span of the plate, were tested with an MTS loading machine which applied a progressively increasing load until the crack started to growth. The critical loads for crack growth and the crack trajectories were found both by theory and experiment.

The experimental results verifying the theoretical predictions. Results obtained from this study indicate that the three-point bend specimen can be used for prediction of mixed-mode crack growth.

Fatigue Crack Growth under Multi-Axial Loading

In the study of crack growth in biaxial fatigue, Sehitoglu et al (1988) investigated the effect of strain state on the nucleating and early growth of fatigue cracks. Thin-walled tubular specimens of Inconel 718 were subjected to combinations of axial and torsional loading in the low-cycle fatigue area were used. The changes in crack growth propagation as a function of crack size has been tested at strain values of 0.01 and 0.005. The following results were made:

- In case of different loading the comparison of crack growth rates will be acceptable if the plasticity levels associated with these cases are similar.

- Crack growth rate for torsional load was found to be comparable to those in axial and combined loading crack growth rates which are depend on similar crack size or strain intensity levels.

- Under pure torsional load deceleration of crack growth rates has been found over a small range of crack sizes and is attributed to the creating of facets along the crack length.

High strain fatigue tests on smooth specimens are carried out for many reasons. For assessment need and design, endurance curves depend on complete specimen severance were used for predicting crack initiation in case of the component is thick compared with the specimen size. In case of specimen size are close to component thickness, failure criterion is needed for component, an earlier definition of failure is sought from the specimen itself.

Turbogenerator and automotive shafts are usually subjected to complex transient torques. Sudden changes in load amplitudes because of line switching of faults in power plants, can subject the turbogenerator shaft to a torque on the order of six to ten times of normal maximum loading. In this case it may be cause to growth of undetected short cracks which nucleated either during manufacturing or after previous faults. According to the growth modes of these short cracks, the turbine shaft may fail in mode I, II, III, or any combination of the three

Generally the analytical models for fatigue crack growth under multi-axial loading have developed slowly due to the lack of helpful closed form solutions for elastic and plastic fracture mechanics under mixed mode I and mode II loading.

With this in mind, Chen and Keer (1991) approached fatigue crack growth analysis in mixed mode loading. In their study a direct approach based on the mixed mode Dugdale model, the accumulated plastic displacement criterion for crack propagation and the cyclic J-integral system is used to develop equations to predict the mixed mode fatigue crack growth. The following assumption was made from their study:

- The total accumulated plastic displacement is the vector sum of the accumulated crack opening displacement and the crack sliding displacement.

Fatigue Failure of contacting Surface

To date, many studies have been done to investigate fatigue failures of contacting components such as bearings and gears. Researchers have classified the contact fatigue failures as pitting failure (the fatigue pit depth $Z \leq 0.1\text{-}0.2$ mm) and spalling fatigue (the fatigue pit depth $0.2 \leq Z \leq 2$ mm). workers assumed that the pitting failure is caused by surface cracks and the spalling failure by subsurface cracks.

A recent study by Chen (1993) indicated that the rolling fatigue failure where fatigue pit depths is 0.1-0.2 mm may cause not only surface cracks but also near-surface cracks which initiate in the plastic deformation layer under the race surface. And a view that the combined action of the high temperature transient yield strength, and contact shear stress result in the plastic deformation layer and near-surface cracks is suggested in this study. According to Chen's analysis of contact temperature and contact stresses it was suggested that "When the race surface of rolling specimen is rough, the contact temperature rise reduces the transient yield strength of the metals below the maximum contact shear stress at this position, thereby, resulting in a plastic deformation layer".

Since the crack closure phenomenon was introduced in the late 1960's by Elber, there has been much argue over the ability of crack closure to account for crack growth rates under variable-amplitude loading, and in particular crack growth retardation following a single peak overload (Fleck, 1989).

Crack Growth Retardation

There is evidence to suggest that the retardation effect associated with a tensile overload occurs because of increased crack closure and a consequent reduction in stress intensity as proposed by Elber (1971; cited by Mcevily and Minakawa 1988). The concept of closure was originally proposed by Elber, who attributed this phenomenon to residual plastic deformation in the wake of the crack. However, the extent of residual plastic deformation in the wake of the crack differs in plane stress as compared with plane strains.

Fleck (1989) studied the influence of stress state on crack growth retardation. Overload tests were performed on thick and thin specimens made from BS4360 50B structural steel. The baseline stress intensity range was 25 $MPam^{1/2}$ and load ratio (minimum load/maximum load of fatigue cycle) was 0.05, while the overload of stress intensity range was 50 $MPam^{1/2}$. It was found that the crack growth and closure responses were various at the surface and in the bulk of thick specimen. And also was concluded that at high baseline ΔK levels approaching the threshold amplitude, retardation can be because of plasticity-induced crack closure or to irregularities of the crack front.

Fatigue crack Growth Under Uniaxial Load

The application of fracture mechanics concepts to the design and analysis of structural components is still under studding. This is due to the inability of translating laboratory information to the design of complex structures.

In a study by Yan and Lei (1994), fatigue growth analysis of an inclined crack under uniaxial cyclic loading in materials with different yield strengths in tension and compression were evaluated.
The purpose of their investigation was an improved strain-energy-density criterion, is extended to the case of cyclic loading to predict mixed-mode fatigue crack growth in materials.
It was found by analysis the fatigue growth of an inclined crack under uniaxial cyclic loading was affected by the ratio of yield strengths in tension and compression. Furthermore, this effect is important if the crack-load-angle is small, and a decreases with the increase in crack-load-angle. However, the effect exists only in the starting step of fatigue crack growth. The fatigue crack growth path often tends to be normal to the load direction whether the crack-load-angle is small or large.

Simple Shear Fatigue Behaviour

Dudlerar et al (1992) performed research on evaluated simple shear fatigue behaviour of solders used to provide both electrical and mechanical inter-connections between electronic components, using specially designed and fabricated simple shear test vehicles and a computer-controlled loading system. They found that both double and single-bump micro-joints, due to their geometry, suffered from a concentration of stress and strain at the positions of smallest cross section. It has been argued that this problem has lead to most of the damage being absorbed in both the tops and bottoms of the barrel-shape-double-bump micro-joints and the bottoms of conical-shaped single micro-joints, thereby concentrating most of the damage in parallel fracture planes in those positions.

Fatigue Striation

Introduction

It is well known that fatigue striation is the most important and dominant microscopic feature of fatigue fracture surfaces in ductile metals and alloys. It rises parallel to the crack front and perpendicular to the direction of crack growth, indicating the successful position of the advancing crack front (Forsyth 1960).

Some researchers have also indicated that striations can both identify fatigue fracture as such and offer significant quantitative data regarding fatigue crack growth rates (Hertzberg 1962, and Pelloux 1964; cited by Ouyang and Yan 1988). Furthermore, the striations can be used to find the propagation direction of the crack, and the relations between growth rate and microstructures, load history, and environment.

Mechanism of Striation

Ouyang and Yan (1988) presented a research on the mechanism of striation formation and fatigue crack growth in engineering alloys. In particular, critical tests were performed on the observation of natural profiles of fracture plateaus and mating fracture surfaces using the scanning electron microscope. It was found that the profile of a fatigue crack shows to be a tunnel with different steps.

Ouyang and Yan (1988) described a model for the mechanism of fatigue crack growth and striation formation under a loading cycle which included four steps:

- Crack-tip opening.
- Shear crack propagation in a short distance by single system slip decohesion.
- Normal crack propagation by alternative conjugate slip decohension.
- Crack-tip closing.

Fatigue crack growth is a continous repetitive process. There is some documentation of the presence of fatigue striations on the fracture surface (e.g Bily 1993) and as shown in Figure (1).

Figure (1)
Fatigue Striations on fracture surface of stainless steel

The striation spacing quite often corresponds to the macroscopic crack length increment per cycle. There are examples in which the striation spacing is lower than the crack length increment. However, there are also instances where the striation spacing is higher than the macroscopic crack length increment per cycle. Fatigue striations are a typical feature of fatigue crack propagation. Even though, the fatigue striation will not cover the entire fracture surface in all metals. There are some materials which are fully covered by the fatigue striation on the fracture surface for example Aluminium alloys and austenitic steels. On the other hand, some materials represent a fatigue surface mainly devoid of areas covered with striations. This is represented in materials which include high strength martensitic steels. However, in such cases crack growth is a frequent process of plastic deformation at the crack tip indicating that fundamental fractures are much the same in all metallic materials.

Crack Closure Damage Accumulation Theory

Rice (1966), and Fine and Davidson (1983) cited by Wang and Thomas Hus (1994) implemented a parameter to calculate the energy necessary to create a cracked area. The energy is obtained by the external load, or in terms of the fracture energy rate (J). For external loading, it was divided into elastic and plastic elements. For elastic energy, it will be released during unloading rather than absorbed by the material. In contrast, plastic energy will remain in the structure of the element and will cause damage which would accumulate to causing an extension of the crack in the case of ductile fracture. Therefore, in many ductile engineering materials the fracture occurs because of accumulation of plastic energy which is higher than the ultimate value in the other hand when the plastic strain energy stored in the material exceeds its limit. The accumulation of plastic strain energy occurs step by step during cyclic loading.

Grids and Interaction of Crystallographic Cracks with Interfaces

Li and Orlekt (1993) presents a methodology for using microgrids on typically oriented bicrystals to study the interaction of crystallographic cracks with interfaces. Aluminum bicrystals of three types were designed to study the effect of the extent of slip incompatibility on crack growth near interfaces.

An inclined notch was cut along the primary slip band at the middle of one edge of each specimen to induce a crack without branching. The methodolog yielded some significant results concerning heterogeneous microstrain at the head of crack tip near interfaces in aluminum bicrystals.
It was found that in crack tip displacements, cyclic shear strain and growth rate are significantly reduced by the interfaces in incompatible bicrystals. An increase of 3.5 mm in PSB width near both crack tip and interface has been detected by comparing grid photographs taken at the minimum and maximum cyclic load, respectively, in a SEM.

The technique shows that incompatible strian induces interface cracks growing slower than transverse cracks in the surface layer in some bicrystal specimens. It was found also that secondary slip system has great effect for increasing the crack opening and tiggering primary slip in the adjacent grian of an incompatible bicrystal.

Effect of Notches on the Fatigue Limit

It is widely known that the fatigue limit of notched metal bodies is usually higher than the value obtaining from the simple application of a stress concentration factor. A large number of approaches have been studied to determine the relation of stress concentration and fatigue notched factor representing the ratio of unnotched and notched fatigue limits has been suggested (Bily 1993). This relation may also be extracted theoretically, as Bily assumed that the fatigue limit is the border between propagation and non-propagation of small cracks with a maximum size l_c (critical short cracks). The scheme for determining the notched fatigue limit is shown in Figure (2).

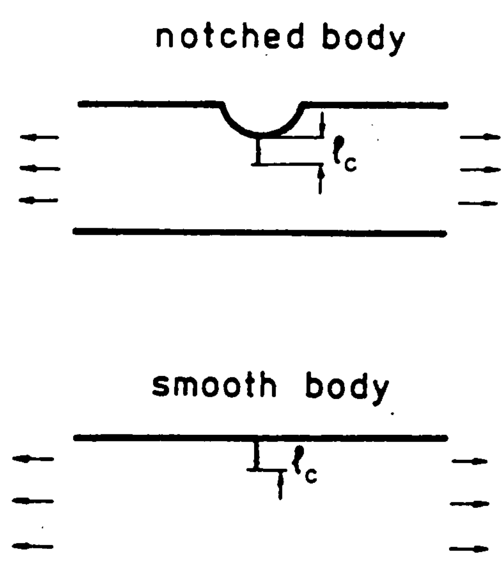


Figure (2)
Scheme for determinition the notched fatigue limit

The stress intensity factors for some cracks concerning notched objects has been suggested by Tada et al (1973).

Stress and Strain Concentration in Notch

Non-homogeneous stress and strain distributions occurs because of the existence of a notch in a loaded specimen. The notch tip increases stress and strain concentrations. In the cyclic straining of bodies with nominally elastic stresses, the amount of strain will rise near the notch tip and this will lead to initiation and propagation of fatigue crack.

Because of difficulties in measuring the stresses and strains in the area close to the notch root, it is normally considered that the local stress and strain amplitude is the same as in a smooth body. it is possible to calculate the local stress and strain for a given zone and shape of a notch by using the tensile stress-strian curve in undirectional straining, and or by the hysteresis loop and or the cyclic stress-strian curve in cyclic straining.

In the case of elastic straining the maximum stress and strain in notch can be calculated from theoretical stress concentration factors (α). The stress concentration factor is the ratio of maximum stress in notch root (σ_N) to nominal stress in the smallest cross-section (σ_n)

$$\alpha = \frac{\sigma N}{\sigma n}$$

Neuber (1958), and Peterson (1953) cited: by Bily (1993) derived approximate expressions for different notches having different ratios of the depth to notch radius.

Application of Stress Intensity Factor

In the early 1960s the application of fracture mechanics to fatigue cracks was considered to be useful in the study of the fatigue process. The fundamental importance of this achievement lies in the fact that the stress intensity factor automatically covers the effect of geometry and thus the dependence of the fatigue crack growth rate on the stress intensity factor will be completely independent of the geometry of the loaded body and of the crack.

The dependence of fatigue crack propagation on the stress intensity factor amplitude can be schematically represented as below in the Figure (3).

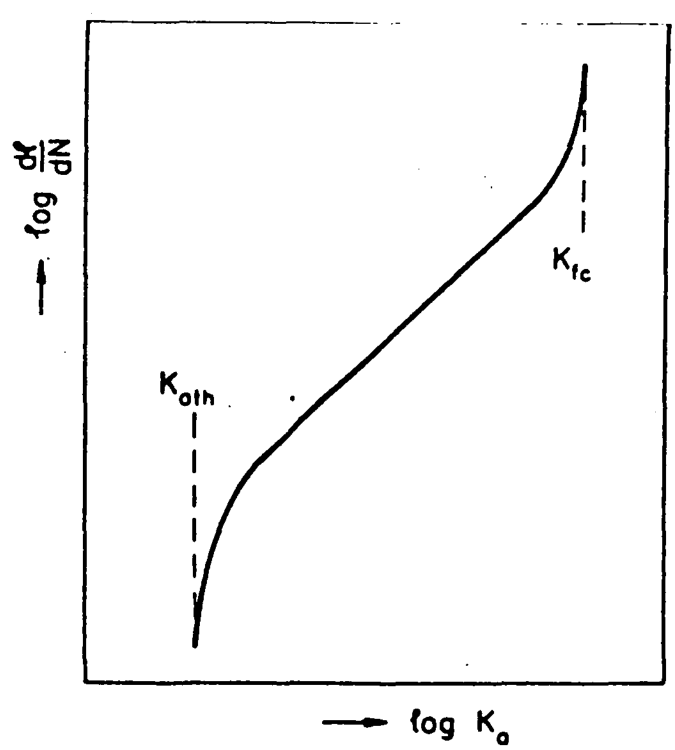


Figure (3)
Scheme of crack propagation rate as a function of stress intensity factor amplitutde

For very low crack growth rate, the degree of independence asymptotically approaches the threshold value of stress intensity factor amplitude K_{ath}, below which no fatigue crack is probable. For very high crack growth rate the dependence asymptomatically approaches the value of fatigue fracture toughness K_{fc}, at which the terminal unstable fracture of the remaining cross-section takes place.

On a log-log plot the middle section of this dependence may always be approximated by a straight line. For instance the dependence is of a power-law type.

The curve which is represented in Figure (3) would be completely independent of geometry or in the meaning curve must be a material curve dependent on the materials (such as environment and temperature), but not on the specimen and crack geometry.

Parameters Influence on the Fatigue

Main parameters of influence on the fatigue process

There are many parameters affects on the fatigue process, they are as follow:

- **Stress raisers.** The strength of fatigue process is highly reduced by the presence of stress raisers for example notches, or keyways, etc. To increase fatigue strength of a metal, it should avoid stress raisers in the structure of metals during manufacturing.

- **Roughness.** According to the experimental work, which have been done by some researchers, they found that smooth surface specimens have high fatigue strength. Rough surface create stress concentrations, which cause fatigue strength to reduce.

- **Surface treatments.** Surface treatments, such surface-hardening for example decarburising, and nitriding, harden the surface of metal, which leads to increase the fatigue strength.

- **Environment.** The chemical environment (corrosion environment) has a great effect on fatigue crack growth. It will speed up the crack propagation during cyclic stress. The combination of cyclic stress and corrosion environment is named by corrosion fatigue.

Effect of grinding on the fatigue damage

Grinding is not always helpful, but usually bad. During the grinding process the temperature of the grinding surface will raise, and that will resulting in plastic deformation in the structure of metal. After that the metal will start to cool which will cause to produce a residual tensile stress at the grinding surface, and that will cause to reduce the fatigue strength. Boyer (1948) has been draw the reduction of fatigue strength due to various amounts of surface grinding.

In additional Davies (1955) shown that the effect of the grinding on the fatigue strength will be reduce when the grinding processes done carefully.

Effect of Heat Treatment on Fatigue Process

Several investigators have examined the effects of heat treatment and test condition on fatigue crack growth. Prater and Coffin (1988) conducted an examination of the intergranular cracking of sensitised stainless steel in high-temperature water. It has been suggested that the effect of crack depth on the rate of a chievieing slow state crack growth rate is highly dependent on both static and cyclic loading at several frequencies at 288 ^{o}C water under chemistry conditions. However prima investigations (eg EPRI, 1983) declared that water chemistry is a promising remedy for intergranular stress corrosion cracking. It is interstaning to recall that further work on this subject is required.

Fatigue Occurrence Under the Effects of Air and Other Environmental Factors

Many experimental investigations have been performed to study fatigue crack retardation behaviour following the application of a single tensile overload. However, most of these information have been carried out in a laboratory environment, and therefore there currently exists a lack of data in corrosive environment which is an important empirical application.

Researchers (Chanani 1978, Wei et al 1980, Tokaji 1983, and following author Tokaji 1984), have been conducted similar experiments on fatigue crack retardation in air and salt water. It seems that they have reached similar conclusions. For example retardation cycles decreased with increasing aggressiveness of the laboratory environment.

The crack growth behaviour following the application of a single tensile overload in 3% saltwater was investigated using a low carbon steel by Tokaji et al (1984). The following conclusions was made:

- The single tensile overload cause delayed in retardation, just as it in air.
- Overload affected area size was not affected by saltwater and indicated the same amplitude in both environments.
- The effect of saltwater on retardation behaviour was not same even in the similar steels.
- Retardation cycles were smaller in 3% saltwater than in air.
- Thinner specimen indicated stronger retardation than thicker one.
- The crack growth behaviour following the application of a single tensile overload in 3% saltwater was more clear by the crack closure system.

Barbangelo (1987) investigated fatigue crack propagation in a steel structure in air or in electronic hydrogen charging environments. They found that fatigue tests and of a fractographic analysis proved that the phenomenon is controlled by the stress distribution at the crack tip. In addition, a transition may happen when the cyclic plastic zone size at the crack tip is larger than the prior austenite grain size.

Fatigue Strength Reduction Factor

The fatigue strength reduction factor, K_f , which is defined as the ratio of the fatigue strength of smooth metals to that of notched metals, has been employed by engineers in the design of notched components of structures. This factor is often lower than the elastic stress concentration factor, K_t, and this difference is more clear for small and sharp notches.

Tanaka and Nakai (1984) proposed a consistent method for predication of fatigue threshold of notched component from three experimental data sets for low carbon steel. These comparisons gave good agreement. Scattering of plastic wave by internal planner crack of mostly general shape happens quite often in quantity non-destructive evaluation. However, there are only a few rigorous solutions to such scattering matters, and these have been extracted almost exclusively for the particular case of scattering from shaped crack. Such earlier researchers include, Mal (1970), Krenk and Schmidt (1982), Martin and Wickham (1983), and Keogh (1983) whose results were compared by Buderk and Acherbach (1988).

Several researchers have been worked on the fatigue behaviour of different materials. As a example Price and Good (1984) declared that the fatigue life time and fracturegraphy compared for nickel and typical nickel based alloys which was tested in liquid mercury and air they pointed out that the fatigue was always less in mercury and it would be different fracture mode would result. Roughly speaking these alloys have quite different characteristics, thus it is predictable that most of these alloys would be affected similarly.

Effect of Corrosive Environment

Corrosion fatigue (CF) decreases the fatigue life of metals and reduces the endurance limit. It is common failure mechanism for materials that work around seawater or corrosive environments.

In general corrosive environment cause to an increase in fatigue crack growth rate. This case not always correct, especially in the near-threshold area. By calling corrosive environment words does not means only strong environment media, but also a mild environments.

Study by Lukās et al (1982) shown in Figure (2) have implemented that also a very mild gaseous environment can affect the fatigue crack growth rate quite effectively.

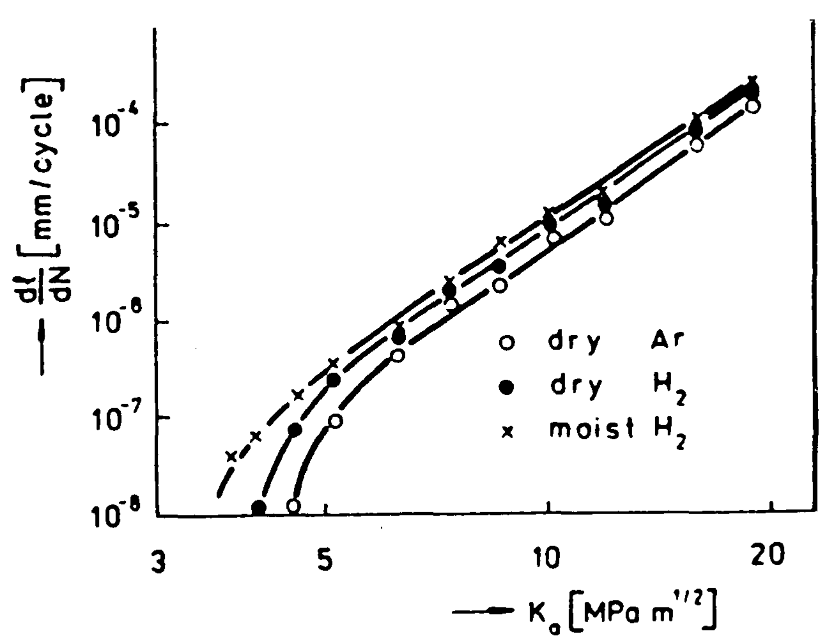


Figure (2)

Effect of gaseous environment on the crack growth rate in stainless steel

Results obtain on stainless steel in dry argon, dry hydrogen and moist hydrogen, as shown in Figure (2), clearly represent that the effect is strong mostly in the near-threshold area.

Many experiments have been performed to evaluate fatigue behaviour under low and high cycles, using different temperatures for different materials in air and corrosive sulfate environments Whitlow et al (1984). They reached to the following conculation:

- The effect of sulfate salt environments reduces the average strian range for 1000-100,000 cycle lifetimes by about 30%, this is due to stress concentrations from pitting corrosion
- The effect of salt environments are even greater (reduce) on the strain range at the low end of the fatigue life scale because of environment embrittlement. For example at 100 cycles the reduction is 59% and at the 10 cycled the reduction is 82%

- Application of the protective coating RT-22 reduces the average strain range in the air by 18% at 1000 cycles and 10% at 100,000 cycles.

Influence of Oxygenated Water on Crack Growth

The influence of oxygenated water on the crack growth rate of sensitised 304 stainless steel is hard to understand, due to existence of two modes of crack growth known to occur in the metal. The first mode , which is trans granular crack growth is normally notes at high frequencies, while the second one, inter granular cracking, happens at low frequencies and under static conditions. The mechanism for intergranular stress corrosion cracking has been studied over many years.

NiCrMoV steels are generally used in the fabrication of high-performance materials and structures such as rotor, pressure vessels, and piping. Usually flaws, machine notches, or micro cracks obtain in the structure of large size material and usually operate under cyclic loading conditions.

Barbangelo (1987) investigated fatigue crack propagation in a NiCrMoV structural steel in air or in electrolytic hydrogen charging environments. The behaviour of this steel containing internal trapped hydrogen absorbed during the steel making processes was considered. They found that the hydrogen, both internal and adsorbed by the environment, causes accelerated crack growth rate. As the loading conditions are changed, two types of damage mechanisms are observed, and are separated by a transition area where the fatigue crack growth rate is constant. The results of fatigue tests and of a fractographic analysis proved that the phenomenon is controlled by the stress distribution at the crack tip. In addition, a transition happen when the cyclic plastic area size at the crack tip is larger than the prior austenite grain size.

Effect of Frequency on Fatigue Crack Growth

Jata et al (1994) examined the frequency effect on fatigue crack growth rates in aluminium alloy 8009 in sheet and extruded product forms. The object of this work was to further investigate the influence of frequency, environment, and creep crack on fatigue crack growth behaviour in alloy in sheet and extruded product shapes. Studies have been performed at two different temperatures of interest, 204 ^{o}C and 315 ^{o}C.The first one was selected being considered as a potential alloy for a number of structural applications near this temperature, and for second one was selected as a higher limit for service for this alloy.

It has been pointed out, a 60 s hold-time at maximum load at 315 ^{o}C leads to retard fatigue crack growth in both, sheet and extrusion. And at maximum load at 204 ^{o}C a 60 s has effect on accelerates crack growth rate in sheet only. For a minimum load it was found that at temperature 315 ^{o}C and 60 s hold time has only a minor effect on fatigue crack growth and no effect at 204 ^{o}C.
From the laboratory air and vacuum tests, it was found that fatigue crack growth rate in vacuum are lower than laboratory air test by a factor of four.

The effect of frequency on fatigue crack propagation has been studied by many researchers.

In this regard Jata et al (1994) evaluated the influence of frequency on the fatigue crack growth rate in laboratory air at different temperatures for a sheet of aluminium, obtained at stress intensity range of 11 MPa $m^{1/2}$.

In the Figure (3) shows that the crack growth rates at room temperature are cycle-dependent over the frequency range at a stress intensity range of 11 MPa $m^{1/2}$.

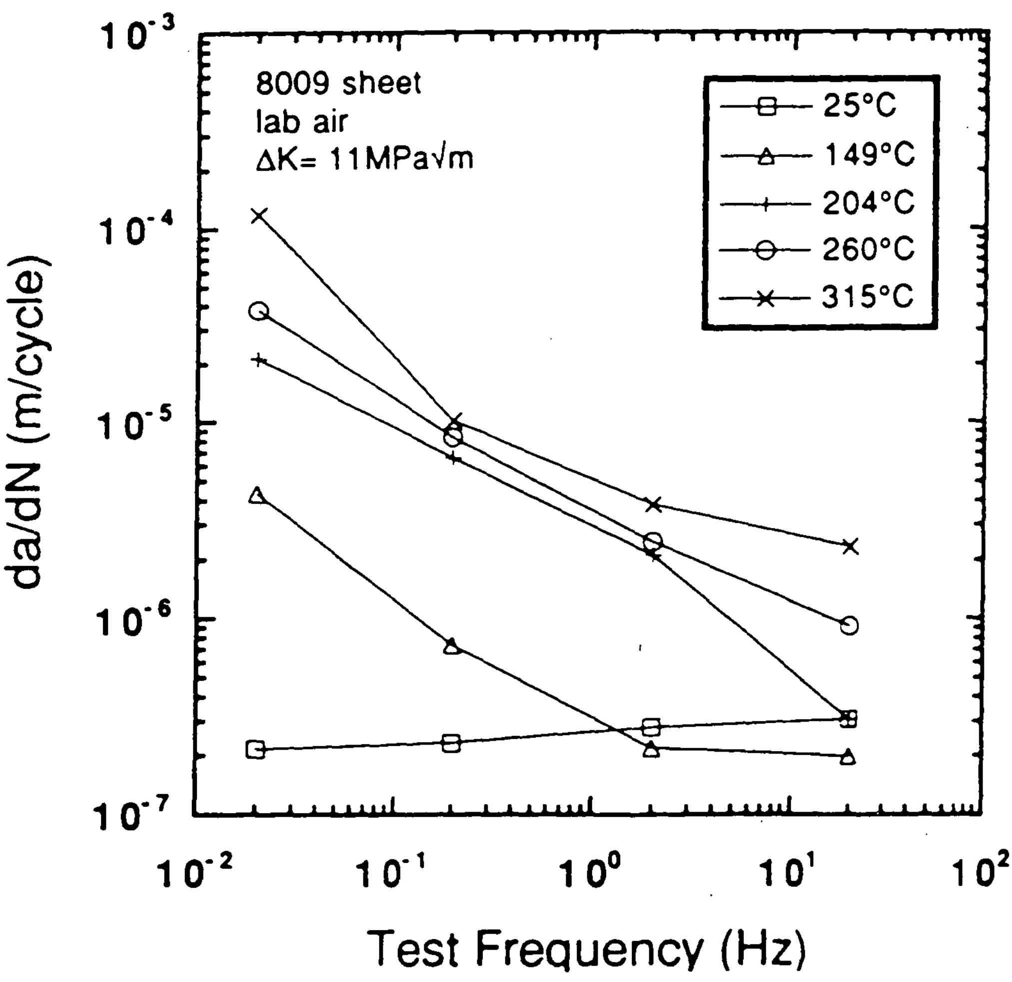


Figure (3)
Effect of frequency on the fatigue crack growth rates in a sheet 8009 at a stress intensity range of 11 MPa $m^{1/2}$

Similarly, the effect of frequency and temperature on the crack rates in aluminium sheet was investigated (see Figure 3). Repeatedly, at this stress intensity range the maximum affect of frequency is observed at 204 °C, the increase in crack growth rate is by a factor of 100 for a decrease in frequency by a factor of 1000. In comparison, crack growth rates increase by factors of 40 and 50 at 260 °C and 315 °C. In addition, the influence of frequency on fatigue crack growth for the 8009 extrusion at 5 MPa $m^{1/2}$ stress intensity is shown in Figure (4). In this Figure maximum effect of frequency is obtained at 204 °C. And increase in crack growth rate is a bout 10 for a decrease in frequency of 10. In case of comparison the influence of frequency is less at 315 °C.

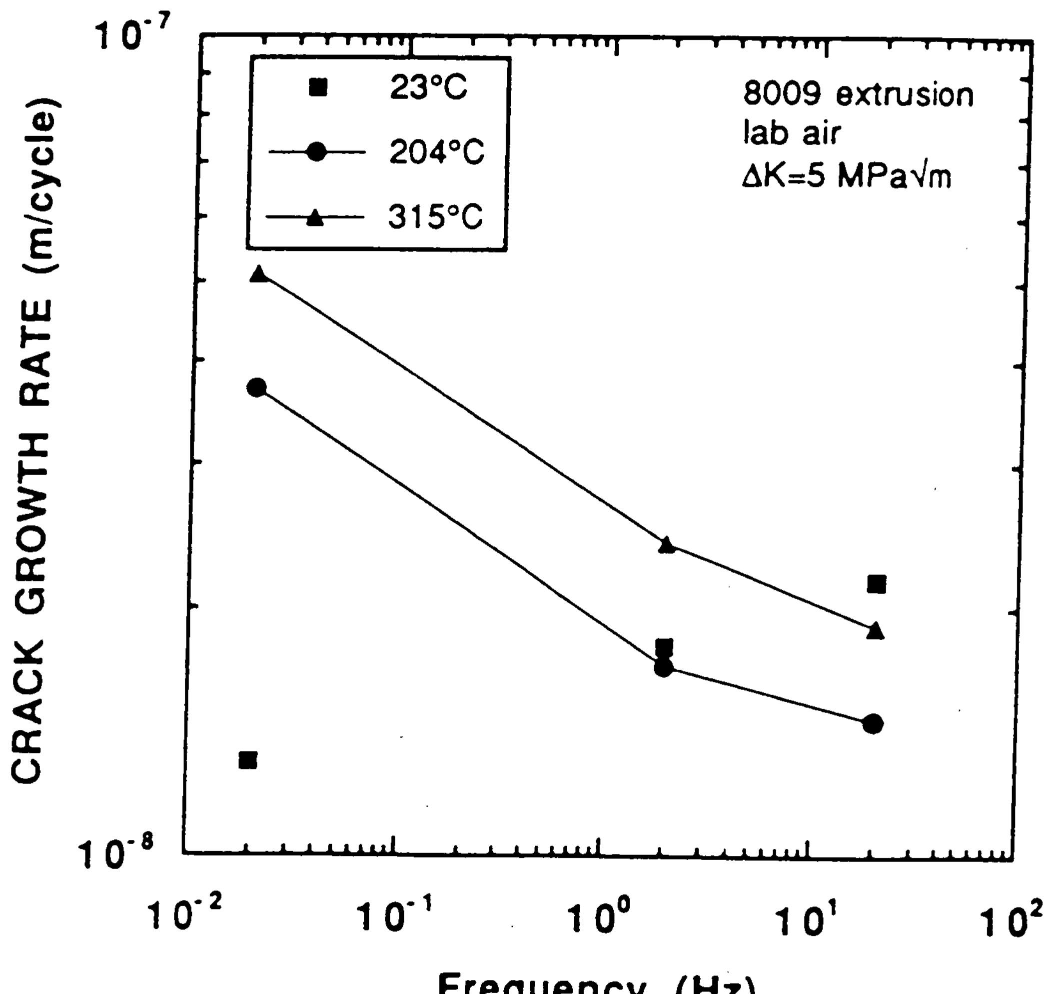


Figure (4)

Effect of frequency on the fatigue crack growth in a extrusion at a stress intensity range of 5 MPa $^{1/2}$

Broadly speaking, these date indicates that at room temperature fatigue crack rates are independent of frequency. However, the affect of frequency at 204 °C is only mild with crack growth rate increasing by a factor of 2 to 3 when frequency is lowered by factor of 1000. Furthermore, the result of undertaking this experiment at the higher stress intensity range of 10 MPa $m^{1/2}$ are shown in Figure (5).

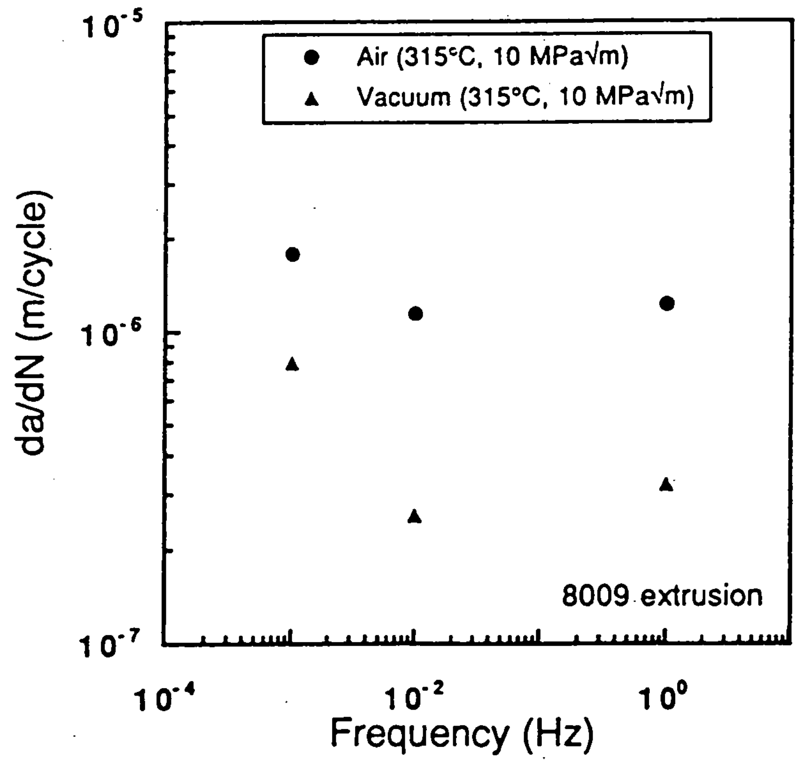


Figure (5)

Effect of frequency on the fatigue crack rates in the extrusion in laboratory air and in vacuum at 315 °C for stress intensity range 10 MPa $m^{1/2}$

In this Figure it is shown that the fatigue crack growth rate in air is not significantly affected by frequency.

The results of investigation shows that in the sheet, crack growth rates at lower frequencies are much faster than in the extrusion. However. when the frequency is 20 HZ, fatigue crack rates are nearly equivalent in the sheet and extrusion aluminium over a range of ΔK of 4 to 20 MPa $m^{1/2}$ (see Figure 6). It is evident that at lower frequencies considerable disparity can be seen in the crack growth rate between sheet and extrusion.

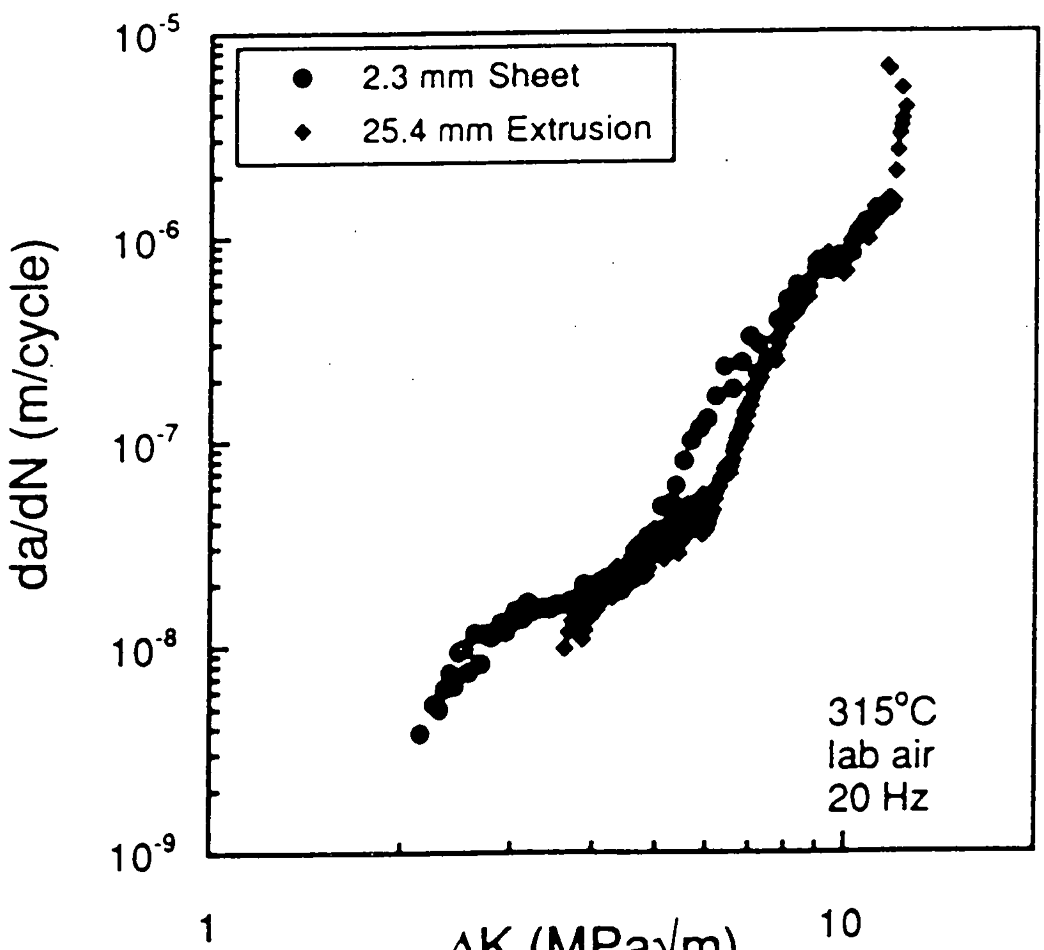


Figure (6)
Comparison of fatigue crack growth rates between the sheet and the extrusion of alloy 8009 at 20 Hz

Several investigators have examined the influences of heat treatment and test environments on the resulting mode of fracture of compact type specimen of 304 stainless steel under cyclic loads (see Hale and Vogelhuber 1977, and Hale et al 1978). From their study they recommended that an environmental controlled frequency influence is present in 304 stainless steel, for example the cyclic crack growth rate increases with decreasing frequency while the cracking mode remains trans granular.

The growth of surface defects in axially loading specimens of sensitised 304 stainless steel was studied under static and cyclic loading at many frequencies in 288 ^{o}C water under hydrogen and oxygen water chemistry environments (Prater and Coffin 1988). Two fracture modes were observed in their study. When the load was static the fracture was intergranular, in case of cyclic load the fracture was trans granular for low cyclic frequencies. Hydrogen additions to water, resulted in great reduced in crack growth rates, and trans granular fracture for all frequencies was observed. Delay in crack growth rates time was observed in surface crack geometry tests when the water chemistry was changed.

Effect of Hold Time on Crack Growth Rate

To understand the effect of hold time on the fatigue crack growth rate behaviour. Jata et al (1994) were implemented test on 8009 extrusion aluminium at 1 Hz with 60 s hold time at P_{max} at 204 ^{o}C and 315 ^{o}C. The result which obtained from these tests for extrusion are compared to the fatigue crack growth rate data with 0 s hold time in the Figure (7a, 7b).

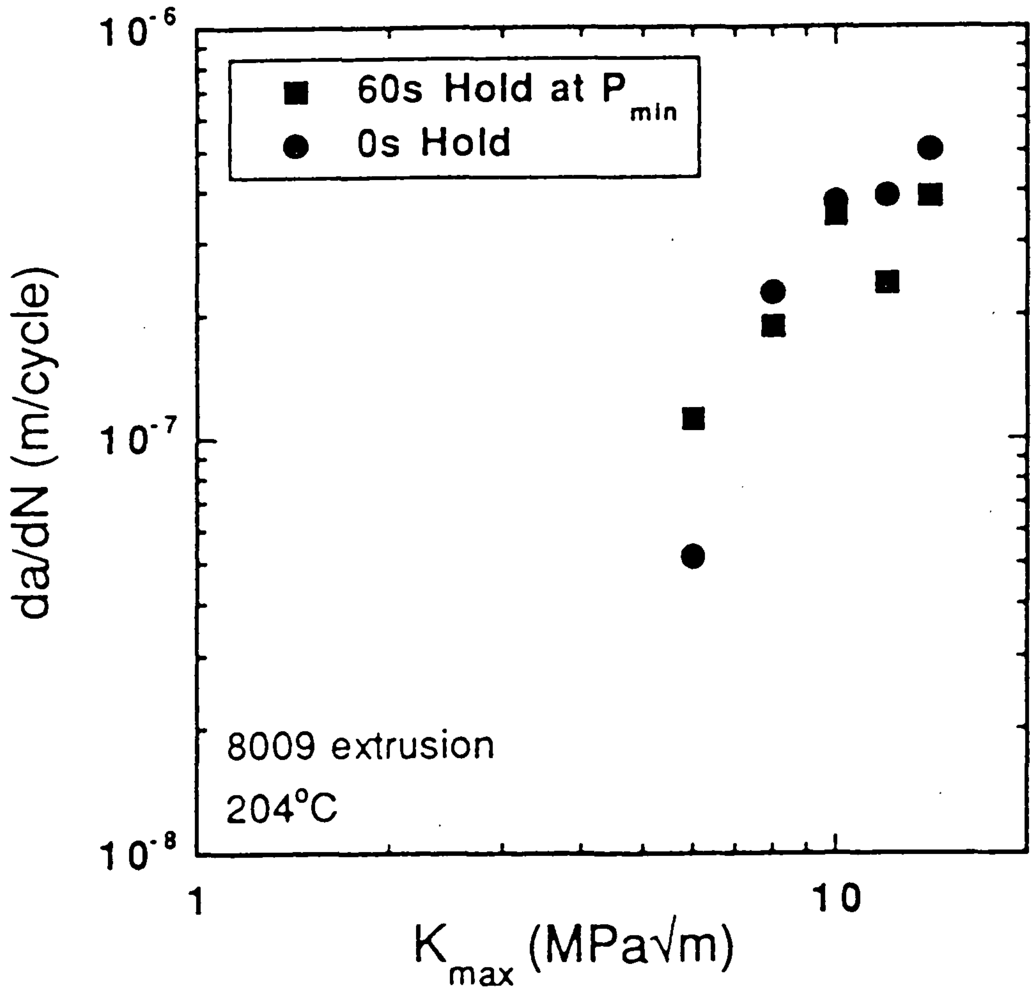


Figure (7a)

Comparison of crack growth rates between pure fatigue under 1 Hz cycling and 60s hold time at P_{max} on the crack rates in the 8009 extrusion at 204 ^{o}C

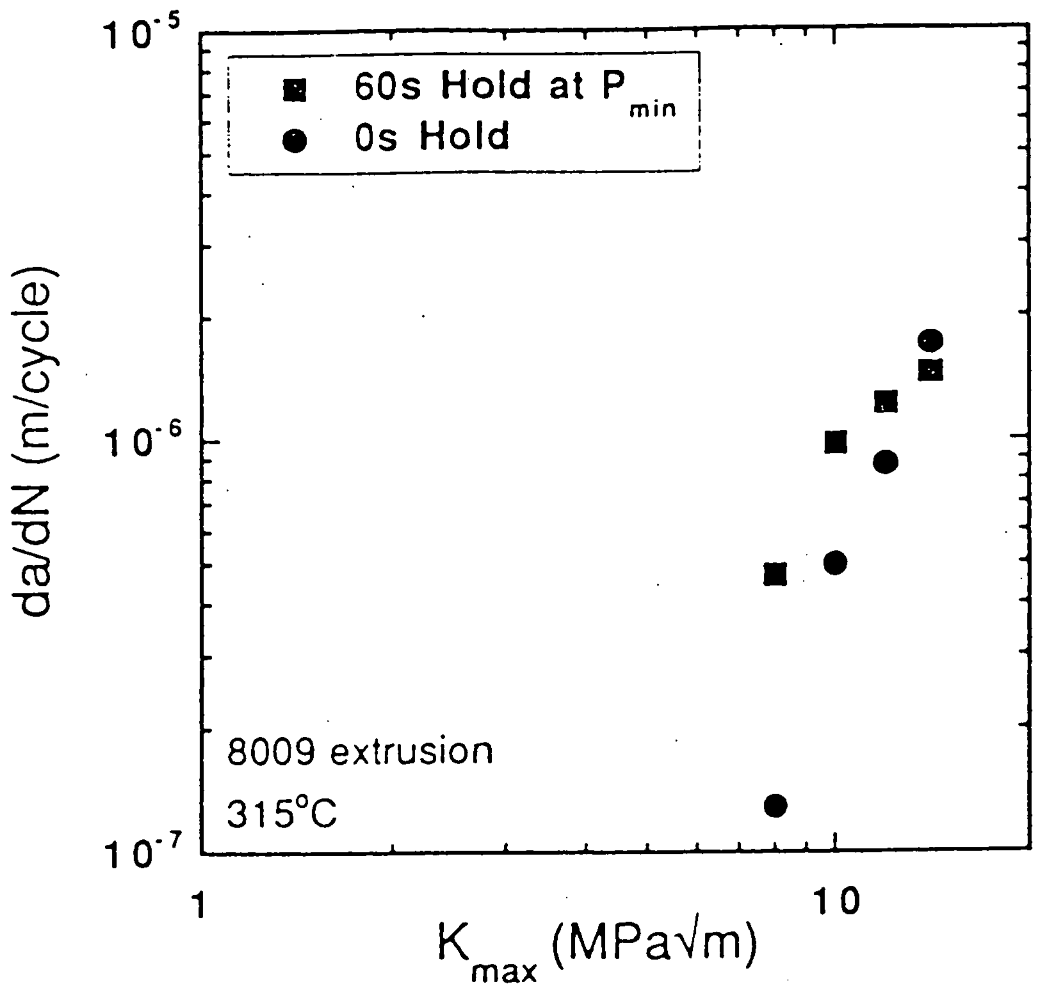


Figure (7b)
Comparison of crack growth rates between pure fatigue under 1 Hz cycling and 60s hold time at P_{max} on the crack rates in the 8009 extrusion at 315 °C

It is evident that at both temperatures, at the some values of K_{max}, the effect of increasing a hold time at maximum load to a fatigue cycle is to retard the crack growth rate. However, the cycle time is increased from 1 s for pure fatigue to 61 s for 1 Hz fatigue with a 60 s hold time.

Temperature and Fatigue Crack Growth

The Effects of Temperature on Fatigue Process

To date a considerable amount of works on thermal-mechanical fatigue life at evaluated temperatures was examined the problem of forecasting the fatigue life of machines components and structures. Some of these investigated the relationship of lives between thermal mechanical and isothermal fatigue at the evaluated temperatures (eg see Sehitoglu and Karasek, 1986; and others 1979; cited by Okazaki and Koizumi, 1987).

Okazaki and Koizumi (1987) studied the surface crack and through crack growth behaviour in thermal-mechanical and isothermal fatigue. Strain-controlled thermal-mechanical and low cycle isothermal fatigue tests were carried out by means of a servo-electro hydraulic test equipment. The cylindrical specimen with a surface or a through notch was used in this study. The length of crack propagating from the notch was measured by a travelling microscope. And the specimen was heated by means of a high frequency induction heating system and cooled by using the compressed air in the specimen core. The following conclusions were obtained from their study;

- The crack propagation rates in thermal-mechanical and isothermal low-cycle fatigue at elevated temperatures were successfully dependent on the range of cyclic J-integral.

- The difference of crack growth rate in both types of fatigue is nearly resulted from the difference of equivalent flow stress.

One of most important parameters which effect on fatigue behaviour is temperature. Very little literature is available on the studying of temperature for steels and aluminium, and few data is available on the effect of low temperature on the fatigue behaviour of both wrought and cast steels (Stephens et al 1984). Low temperature fatigue behaviour is usually considered to be better than room temperature (Forrest 1967, Mann 1967).

The aim of the study performed by Stepens et al (1984) was to obtain both constant and variable value fatigue behaviour of five alloys (low carbon steels) used in the vehicle industries at both room and low temperature (-45 ^{o}C). They found that the fatigue resistance at low temperature was often equal to or better than at the room temperate.

Similarly, Stephens et al (1985) analysed fatigue crack growth analysis in five cast steels at room temperature and at -45 ^{o}C to explain more fully threshold and near threshold constant amplitude fatigue crack growth rate at these temperatures.

Tapsell (1925) indicated that high-temperature alloys is defined as a material which is suitable for resisting reasonable fatigue stresses at temperatures above 500 ^{o}C. This definition includes most alloys like aluminium, magnesium, copper and titanium alloys, and also included most of ferrous alloys.

The most published data on the fatigue properties of high-temperature alloys at elevated temperatures have been determined with a reversed bending or a tension compression (pull-push) stress. And the test specimen which is used for fatigue tests at elevated temperatures is similar to that used at room temperature.

The prediction of fatigue damage is an important matter in the manufacturing engineering. Unfortunately, many engineering components involve loading that is more complex than uniaxial loading. An example of complex loading is shaft subjected to twisting and bending stress. For this case different types of machines have been developed including tension-torsion, internal and external pressure, torsion and bending in order to measure the biaxial fatigue tests at elevated temperatures.

Jordan and Chan (1987) implemented an experiment to investigate fatigue behaviour at elevated temperatures above 649 ^{o}C. Jordan and Chan used a large commercial die set as a load frame. And biaxial extensometer based on capacitance displacement probes works well provided local heating methods (induction, band heaters, etc) are used. For specimen heating used clamp-on band heaters outside of the gauge length which provided satisfactory temperature distribution up to 649 ^{o}C, and an internal heater was used to improve the temperature profile. From this test it was clear that for specimen geometry used here, any crack-tip heating because of induction heating has no important effect on the fatigue life. And the following considerations was observed from this study;

- A single test applying induction heating in the torsion test performed high difference. From the test run applying band heaters. It recommended that the effect of any crack-tip heating was not significant for the metal and life range considered.

- Strain-gauge experiments at room temperature recommend that in certain cases at least should be considered.

High temperatures have large influences on the behaviour of metals. These influences can be reducing of strength, increased or decreased fracture ductility, and decreased fatigue life.

Krukemyer et al (1994) conducted an experimental investigation on 22Cr-20Ni-18Co-Fe alloy in order to study the fatigue behaviour of the materials at elevated temperatures. Fatigue experiments were carried out at constant temperatures ranging from room temperature to 871 ^{o}C with strain ranges from 0.265 to 1.5% resulting in lives between 10^2 and 10^6 cycles. Cyclic deformation properties were evaluated depended on fatigue data. Three fatigue life models were evaluated for their ability to predict the isothermal fatigue lives of the materials. These methods are Ostergren, Frequency Separation and Stress-Strain-Time models. The material used for this study was Haynes alloy 556 (the chemical composition of this material showing its high Ni, Cr, and Co content). The following conclusions were made from their study;

- The stress response of Haynes alloy 556 generally stabilises by the half-life particularly at the higher temperatures. However, slight hardening of the material at 300 and 500 ^{O}C continues to fracture.

- At temperatures of 500, 750, and 871 ^{O}C deformation mechanism changes are agree to happen between high and low strain ranges.

- Bernstein's Stress-Strain-Time model was able to predict the low cycle fatigue data better than Coffin's Frequency separation or Ostergren's Hysteresis energy model. Bernstein's model is more difficult to use due to the large number of variables.

Similarly to Krukemyer et al's research, Wakai et al (1993) assesses high-temperature low-cycle fatigue of the type 304 stainless steel and alloy 718 superalloy friction-welded metals were studied in order to obtain the fatigue strength of the joints. The following results were obtained;

- They observed that the metals with type 304 welded have inferior fatigue strength in comparison with the base metal. The fracture part of the welded metal was the weld interface at the large strain range while it was base metal 3-4 mm apart from the interface at the small strain range.

- Low cycle fatigue lives of alloy 718 welded metals exhibit fatigue strength equivalent to those of the base metal. the hardness of the interface was clearly reduced by the welding process. In spite, the softening had no effect on fatigue life. The cyclic softening and large yield stress were the main reason of the large fatigue life of the welded metal.

The high temperature low-cycle fatigue and creep-fatigue behaviour of AISI 316 steel, which is of great interest for several high-reliability components, especially in the nuclear industries, has been extensively approached in recent years.

Manfredi and Vitale (1989) reviewed the experimental activities in the field of life assessment under high temperature low-cycle fatigue and creep-fatigue behaviour in AISI 316 weldments. These activities carried out in air, under either uniaxial or biaxial loading conditions, at 550 ^{o}C and 650 ^{o}C.

Levin and Karlsson (1991) investigated the fatigue crack growth properties of an aluminium AA 6061 alloy containing 15 vol% particular SIC and of the corresponding matrix alloy with the same grain size. This composite was examined in the undeformed condition and after undertaking a plastic restrain of 0.33% which changes the residual micro stress position of the matrix from hydrostatic tension to longitudinal compression. The following conclusions were made from their investigation:

- Prestrained and undeformed composites exhibit improved fatigue crack propagation resistance compared with the aluminium alloy.

- The SIC particles leads to crack deflection thus improving roughness induced crack closure compared with that in the matrix alloy.

- The higher real crack growth resistance in the composite material is leaded partly by relief of the effective stress intensity as a result of angular deviations of the crack tip and partly by the reduction of the effective crack tip opening displacement.

- Prestraining of the composite result in a twofold increase of crack closure stress intensity, the reason for which is at present not understood.

- The real resistance to fatigue crack propagation in the composite is unaffected by prestraining.

Fatigue Test at Elevated Temperature

In general fatigue crack growth increases with increasing temperature, in which the cyclic deformation at the crack tip is easier. Study by Lukās et al (1982) on the effect of higher temperature on the crack growth rate of stainless steel is shown in the Figure (1).

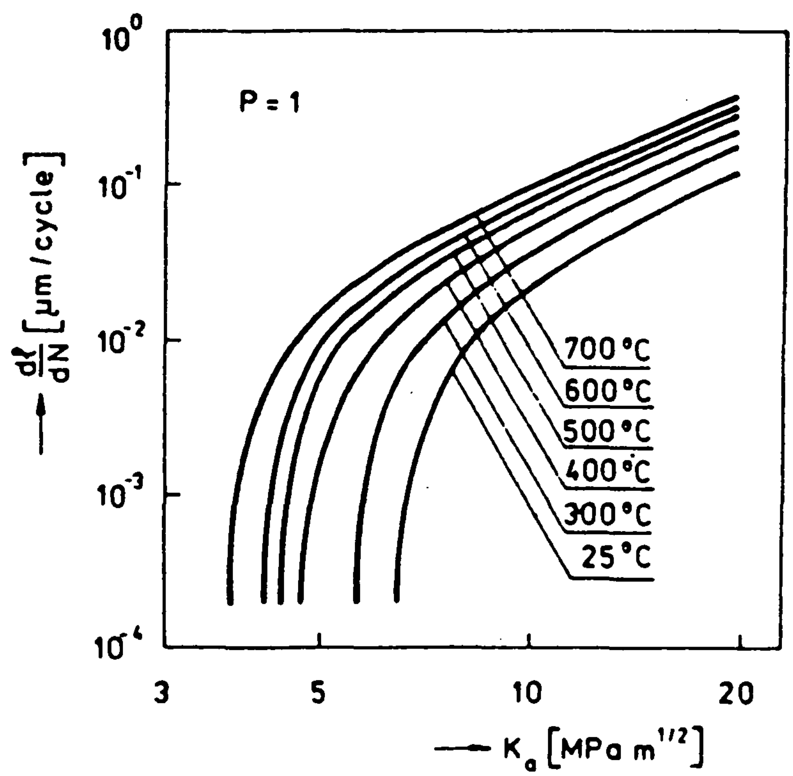


Figure (1)
Effect of high temperature on the crack growth rate
in stainless steel

In this figure we can see that for constant value of stress intensity factor, the fatigue crack growth rate increases with increasing temperature.

Fatigue tests have been conducted at elevated temperatures over the last two decades. Unwin (1906), using the fatigue test for rotating and bending on mild steel, showed that fatigue properties were slowly improved with increases in testing temperature up to 230 ^{o}C. Further data on elevated temperature were given prior to 1925 by Howard, Hankins, Batson and Hyde, Mason and Lea, and Budgen. These tests were implemented on low-alloy steels or aluminium alloys.

Data on the fatigue properties of high-temperature alloys at elevated temperatures have been calculated by using reverse stress for bending or compression-tension (push-pull) stress. For the tension-compression test, the Haigh machine, which has stationary test piece, was used. For the rotating test, a Wöhler type machine was used, and many different kinds of equipment were used to measure the accuracy of test piece temperature.

Specimens usually used for fatigue testing at elevated temperatures, are the same as those used at room temperature. That is to say the critical section is solid, and for a tension-compression (push-pull) stress where the stress is uniform across the critical section this appears to be satisfactory, providing uniform temperature across the critical section will be uniform across the critical section.
Therefore, when the latter condition is not achieved then thermal stresses will be superimposed on the applied stress. In the case of a reversed bending test, where stress is not uniform across the specimen, any plastic deformation which occurs on the surface during the test will produce a redistribution of stress across the specimen.
This condition occurs mainly during the high temperature test and will have an effect on fatigue failure properties which will be higher than tension-compression test properties.

In the study of Manson-Coffin curve shown in Figure (2), shows the behaviour of low-carbon steel at room temperature and at 350 ^{o}C.

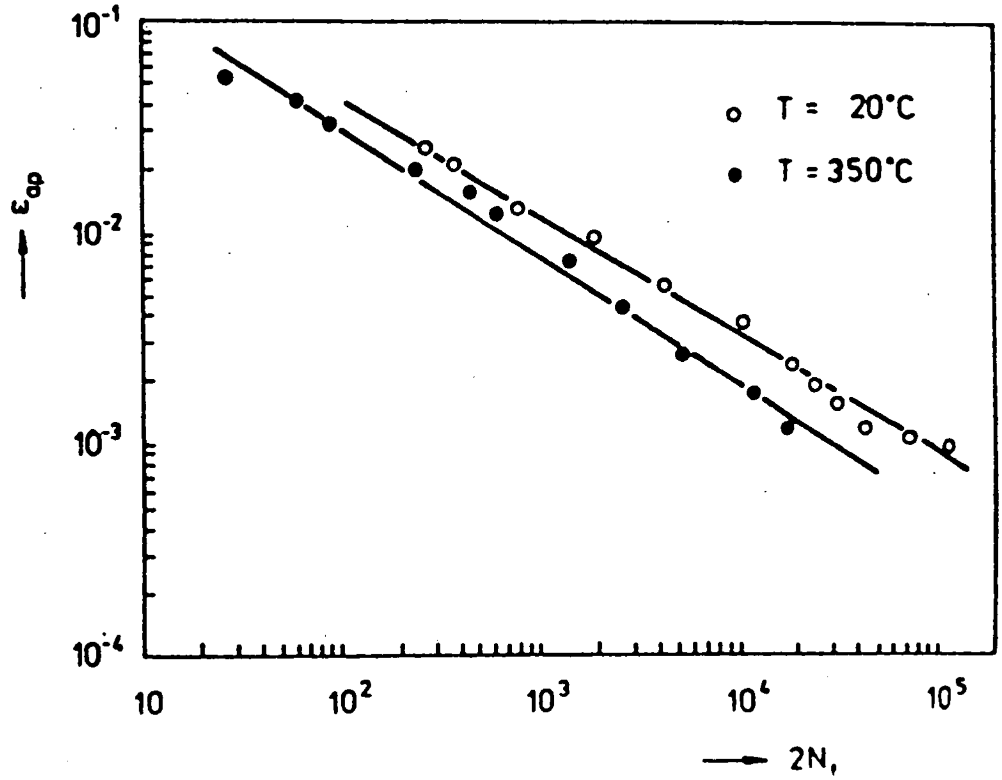


Figure (2)
Manson-Coffin curve of Low-carbon steel at room temperature and elevated temperature

This figure is shown approximately the same slop for both cases which is characterised by the same fatigue ductility exponent, the only difference being that the curve for 350 ^{o}C is shifted to lower fatigue life.

Many studies have been carried out on the effect of temperature on the fatigue life, Berling (1969) has investigated austenitic stainless steel, and later super alloys especially nickel and cobalt-bases were investigated by Coffin (1972).

Material response in high-temperature can be controlled by the deformation processes, such as time-dependent creep and time-independent plasticity during either tension and compression straining in the fatigue cycle.

One of the most successful methods for predicting high temperature, low cycle fatigue life is the strain-range partitioning method, which was developed at NASA and has become a viable engineering design tool, the procedure involves the practical determination of the four basic life relationships, resulting from the four possible integrations of plastic or creep strain range in the tensile test of the fatigue cycle for the material under investigation. They used in cooperation with interaction damage rule to predict cyclic lives.

Effect of Low Temperature on the Fatigue Crack Propagation

Many factors such as temperature, strain rate and corrosive environment affect low-cycle fatigue life. The more affected factor on the fatigue life is temperature.

lowering the temperature of many materials will result in increasing cyclic stress (Polak 1982), as a result of hard dislocation motion. The initiation of fatigue crack can be affected by temperature due to the different character of the slip. Mughrabi (1979), Magnin (1979), and Driver (1980) all cited: by Bily (1993), found that metals with body centre cubic (BCC) phase at room temperature with cyclic straining mostly leads to inter crystalline cracking by increasing the strain rate. So by increasing the strain and decreasing the temperature resulted in an increasing in effective stress. Lowering the temperature of metals causes to growing fraction of inter crystalline crack.

Polăk and Klesnil (1976) have been studied the effect of low temperatures on the low-carbon steel. In the Figure (3) shows the Manson-Coffin curves for low-carbon steel at two different temperatures .

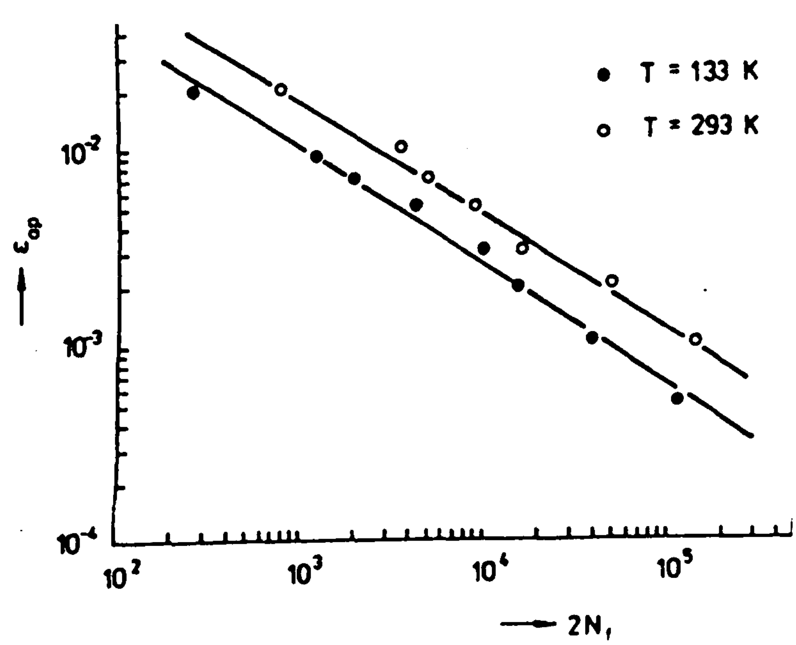


Figure (3)

Manson-Coffin curves for low-carbon steel at two different temperatures

In the analysing the effect of temperature on the cyclic plasticity, It is important to consider separately the temperature zone where the dislocation structures are stable with time and the temperature zone where the hold periods have comprehensive effect on the dislocation structures. For most metallic materials, the dislocation structure at low and room temperatures is stable and recovery begins at elevated temperatures. The effect of low temperature on cyclic plasticity differs for different crystalline structures. The fatigue hardening and softening curves and the cyclic stress-strain of poly crystalline copper at temperatures of 293K and 78K were measured by Feltner and Laird (1967); cited by Bily, (1993).

A marked increase in stress amplitude with decreasing temperature was discovered. The cyclic stress response in cycling poly-crystalline copper at different temperatures can be illustrated in Figure (4).

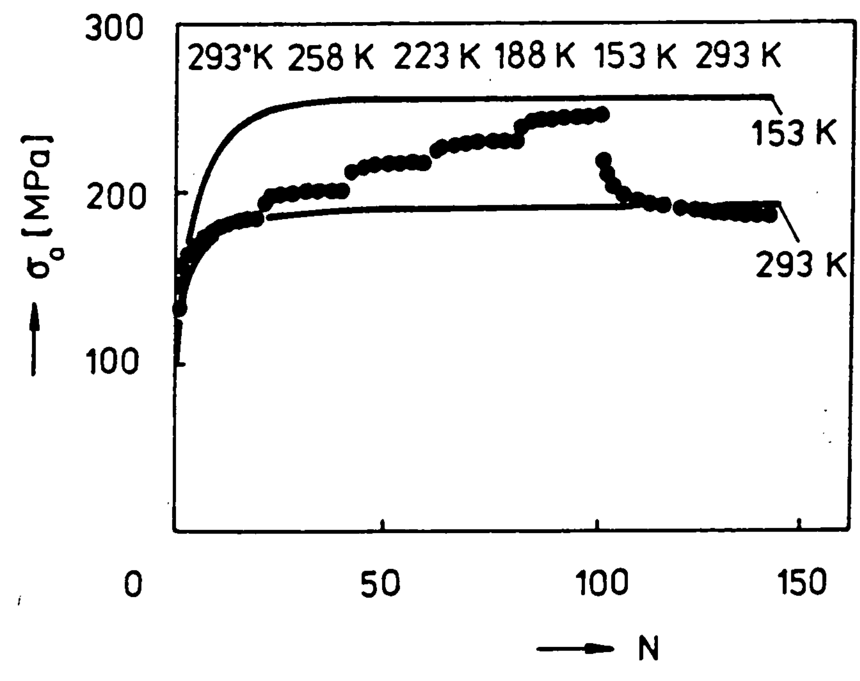


Figure (4)
Various of stress value because of change in cycling temperature in poly crystalline copper

In general the lower temperature leads to a lower fatigue crack propagation rate. As we mentioned that the basic mechanism of fatigue crack growth is the repetitive process of cyclic deformation at the crack tip. This mechanism manifests itself by striations on the fracture surface. In the brittle type of fatigue crack propagation, manifests itself by smooth cleavage facets on the fracture surface. The fact that there are two types of competitive processes of fatigue crack propagation, which is plastic type and cleavage type, which leads the temperature dependence of the fatigue crack propagation rate totally dependent on the material, for example austenitic steel will not transit to brittle fracture with decreasing temperature, and no detrimental effect of lower temperatures can be observed. In case of transition behaviour of steels (like transition to brittle fracture at low temperature), the curve of fatigue crack propagation rate is strongly dependent on temperature.

Study by Lukãs et al (1982) on the effect of low temperature on crack growth rate in stainless steel which is shown in Figure (6).

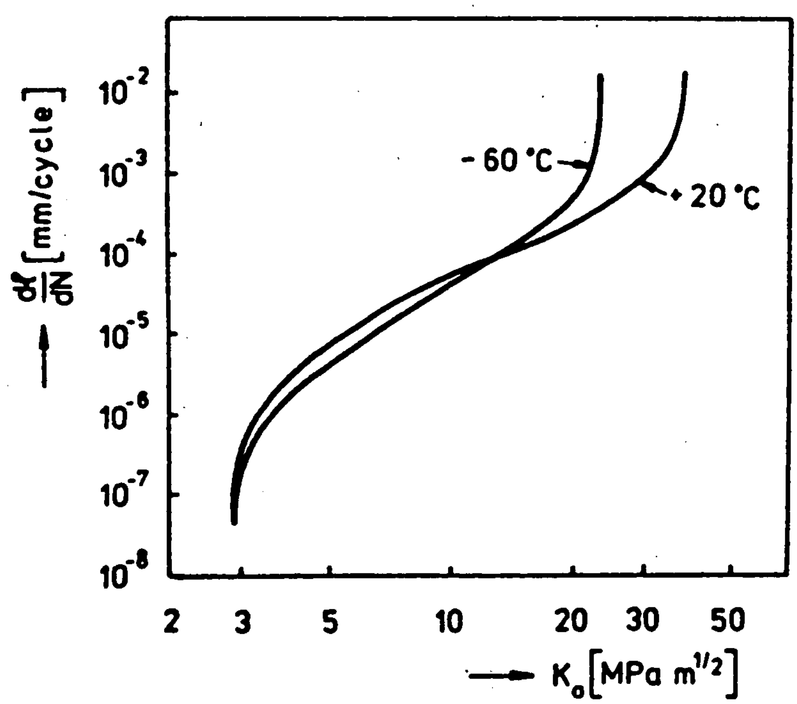


Figure (6)
Effect of low temperature on crack growth rate in stainless steel

In this Figure the spring steel was tested at room temperature and at -60 ^{o}C. It can be seen, that the near-threshold and the centre area of the curve is not much affected by temperature, on the other hand the area of crack growth rates is affected totally by temperature.

Near-Threshold Fatigue Crack Growth

Fatigue in the Near-Threshold Area

Fatigue crack growth in the near-threshold area is usually important in determining the fatigue lives of engineering components and structures. Behaviour in low strain-strength structural steel is of particular interest due to wide use of materials of this type in engineering applications. In spite of, many studies of effects of variables such as micro-structure, load ratio, temperature, and environment, clear understanding of the mechanisms of near-threshold propagation and the parameters controlling them has not been found.

Kendall and Knott (1988) have addressed mechanisms of near-threshold fatigue crack growth by comparing behaviour in air and vacuum in low-strength structural steel. And also they examined the ways in which this is affected by environment, load ratio, temperature, and grain size. They found that the crack growth rates are lower in a vacuum than in the laboratory air, and that the threshold increases with increasing grain size in both environments. Values of surface roughness are shown in Figure (1).

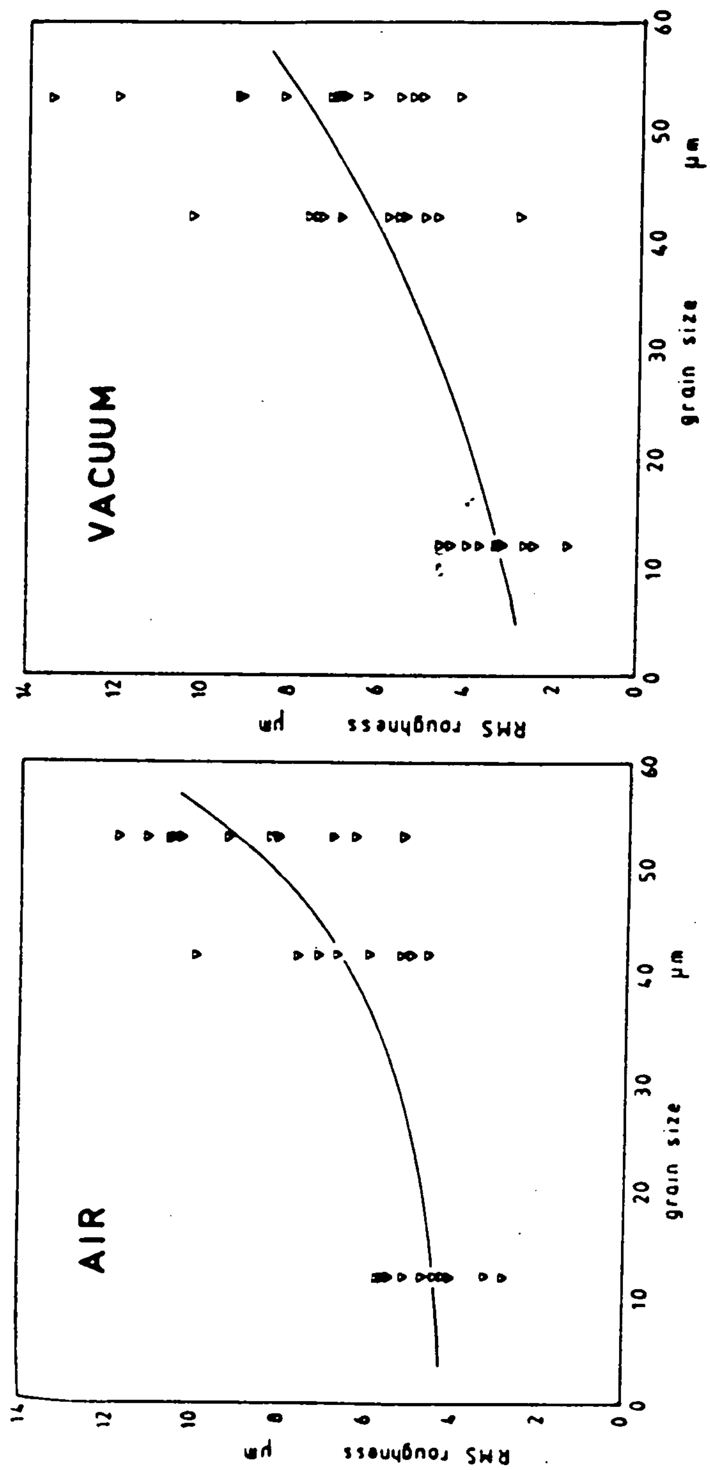
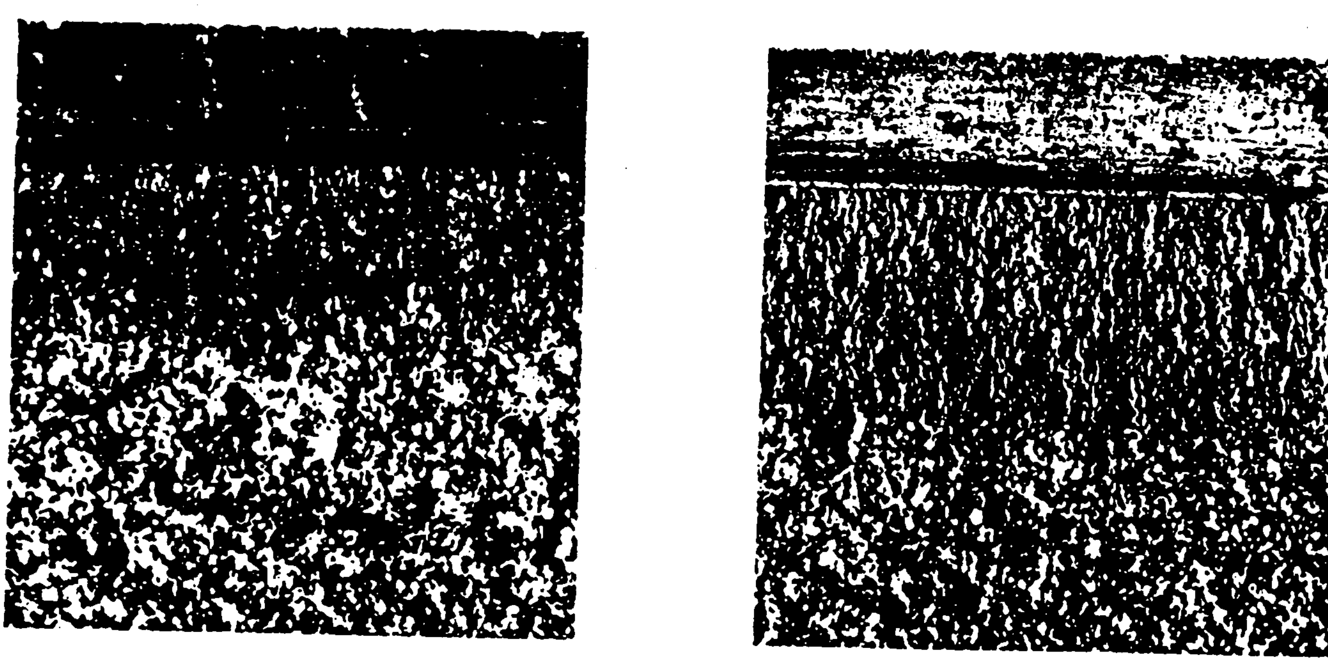


Figure (1)
Fracture surface roughness in air and vacuum

For a given grain size, the roughness in a vacuum is not considerably different from that in air. However, as grain size is increased, the roughness increases in both air and in vacuum. Therefore, increased values of crack in a vacuum may not be attributed to any affect of surface roughness.

Also they found a dark band at threshold on the fatigue surfaces of all metals tested in air, but not on any of those tested in vacuum see Figure (2).



a b

Figure (2)
Oxide on fracture surface in a) air, b) vacuum

Similar band was found by Suresh et al (1981), and also by Gray et al (1983) in steels and identified as hydrated iron oxide ($Fe_2 O_3 . xH_2 O$). The effect of oxide behind the crack tip is to produce a wedging action which increases the measured value of ΔK_{th} which is explain the fact that the ΔK_{th} is higher in a moist gaseous environment than in a dry environment.

Nagase et al (1993) employed an aluminium foil to measure surface roughness during the fatigue process with regard to variable amplitude stress. They found that constant mean stress would not affect surface roughness. It was found that the aluminium foil could be use as the range-pair counting fatigue gauge with high accuracy.

Methods for Increase Fatigue Resistance

An important need for increase resistance to fatigue in the metal is a structure that stops slip of structure. Since fatigue is overwhelmingly a surface phenomenon the condition of the surface is especially important. It is important to get hard surface layer which is resists slip, rather than soft surface layers. Hardening and strain ageing, a lower elastic modulus in the layer could be necessary. A pre-straining method that causes compressive stresses in the surface should be useful. It is usually considered that some of the beneficial effect of shot peening are also necessary. Furthermore, there should be no paths of weak cohesion along which crack can grow easily.

In design a against fatigue failure, the initiation controlled approach aims at determining a stress level below which failure will not happen. On the other side, the damage tolerance approach aims at predicting fatigue life by studying the history of growing cracks. Notch same stress-risers happen widely in engineering materials. In the controlled design approach; it is usually considered that for a notch, the stress concentration factor will be a reasonable factor to calculate the stress value.

Research undertaken by Biner and Yuhas (1989) conducted a study on growth of short fatigue cracks at notched with root radius ranging from 1.6 to 6.35mm at different depths in woven fibber-glass reinforced polymeric composites. It was found that the initiation and propagation rate of short cracks starting from blunt notches can be accurately explained by an effective stress intensity factor range. The results provide an adequate engineering approach for design against failure from range of stress concentrations, at least for this composite system.

Fatigue Life of Sheet Structures

The structural integrity and the reliability of sheet structures, particularly those of high risk like pressure vessels and pipes, is an important topic for many researchers (see eg Kaufman et al 1980, Czoboly et al 1989, Rajab and Zahoor 1989).

Toribio and Valiente (1993) offers an engineering approach to calculate the fatigue life of sheet structures under cyclic loading.

Manfredi and Vitate (1989) comprehensively reviewed experimental activities regarding life time assessment of fatigue under high temperatures, low cycle fatigue and creep fatigue condition in welded metals. The following conclusion were drawn:

- The effect of various of cyclic material characteristics across the welded area can be dismissed in design application.

- Property variation between 550 ^{o}C and 650 ^{o}C is mostly negligible under monitoring loading, but becomes significant when materials are cyclically stresses. The use of high strength material is usual in latest airplanes, but these materials are very sensitive to flaws and defects.

Crack Length Measurements

Recent aerospace vehicles encounter variable mechanical loads and thermal variations. Thus crack propagation measurement are needed.
Recent systems for calculating crack length are based on measurements of physical quantities for example strain potential drop. Any changes in these quantities it means the changes in crack length.

Kirchner et al (1988) presents new techniques of crack length measurement. Two crack-sensor technologies dependent on laser and X-ray directions have the potential to meet the requirements for automated crack-length measurements at high temperature.

They found that crack-length measurement for both the laser and X-ray techniques were viable, and the laser technique was chosen due to wider performance for further system implementation considerations.

Biaxial Low Cycle Fatigue

Investigations of biaxial low cycle fatigue are an important area from the viewpoint of not only the basic study of the mechanical behaviour of the metal in biaxial stress but also design criteria of some applications since they mostly suffer biaxial loading. Many investigations of biaxial fatigue have been carried out (see eg Crimple 1974).

Snake et al (1988) conducted a research to study biaxial low cycle fatigue for notched, pre cracked, and smooth hollow cylindrical specimens of type 304 stainless steel at high temperatures in air. Push-Pull and reversed torsion tests were used. The crack direction in the three kinds of metals and the parameters that correlates the biaxial low cycle fatigue failure data were studied. The results showed that all types of metals, except the smooth metal in the reserved torsion test, failed by mode I (predicated metal) cracking. The equivalent stress based on crack opening displacement (COD) technique might correlate with the biaxial fatigue data; however the principal stress would not satisfy the requirements.

Fatigue Life of Metals under Multi axial Loading Condition

In the investigation of fatigue life of metals under multi axial loading condition, it has been found in recent years that the effect of path-dependence must play an important role. Most of experimental work in this area have been implemented through out-of-phase fatigue loading conditions (it can be obtained by applying axial push-pull and torque with a phase angle between them using tubular specimens), which cause to either detrimental or beneficial effect as compared to proportional loading, depending on the value of the cyclic test.

Wu and Yang (1987) performed a set of strain-controlling experiments on tubular specimens of annealed stainless steel. Three important factors of low-cycle fatigue test have been studied, which are fatigue life, the crack initiation, and the crack propagation. The effect of strain-path on these factors have been studied experimentally using automatiated MTS axial-torsional materials test machine. The following conclusions was made from their investigation:

- Path-dependence is an important factor in the studying of the fatigue fracture, which affect the fatigue life, the direction of initial crack, and the direction subsequent crack propagation.

- Fatigue life will be longest for the case of pure torsion and shortest for pure axial straining for the same equivalent strain range.

- Crack initiation is usually in the tensile mode for even for pure shear straining.

- SEM is important in the identification of the site of crack initiation.

Fatigue Strength of Materials

A number of previous data on the fatigue strength of materials have been found by rotating, bending fatigue test, due to high stability and simplicity of testing machine. The most important factor is to be considered is the magnitude of normal component of stress on the maximum shear stress plane, or on the plane at which a crack initiates. In case of crack is exist in a material, the ratio of the torsional fatigue stress to the rotating bending fatigue strength will be different from undefected plane specimen.

This is because the propagation of cracks emanating from a defect depends on its size. shape and orientation, though the cracks of a plain specimens nucleate along the plane of the maximum shearing stress. The problem is related to the multi axial, mixed mode or non mode (I) fatigue crack growth threshold and the research in this area is becoming progressively active (Endo and Murakami 1987).

Effect of Defect on Torsional Fatigue Strength

Endo and Murakami (1987) investigated the effect of small defect on torsional fatigue strength from the view point of previous research on rotating, bending fatigue. Reversed torsion tests were carried out on 0.46% carbon steel specimens with a small hole of 40, 50, 80, 100, 200, 500 μm in diameter It was concluded that:

- The torsional fatigue strength is found in accordance with the alternative of the two fracture modes; one is fracture caused by the crack which is start at the hole edge and then propagated in ±45 deg direction to the axis and the other is that caused by cracks which nucleates along the rolled layer in the axial direction.

- Hole diameter is above 200 μm, the hole became the fracture origin, while when the hole diameter is less than 100 μm cracks start on the other surface sites rather than the hole edge and the cracks became the fracture origin, so the critical diameter which is found to bounds two fracture modes is approximately 130 μm.

- The maximum size of non propagating cracks observed on the plain specimens with 0.46% carbon was about 50 μm in rotating bending and about 500 μm in torsion. In the case of specimen with 13% carbon, it was about 100 μm in rotating bending and about 1000 μm in torsion. The existence of large non propagating cracks in torsion is correlated to the fact that cracks have trend to grow along rolled ferritic layers sandwiched between pearlitic layers for both 0.46% and 13% carbon steels.

Low-Cycle Fatigue

In general low-cycle fatigue is described as when the number of cycles to fatigue is less than 100,000 cycles, or when the plastic strain range is larger than the elastic strain range (Bernstein and Loeby, 1988).
Low cycle fatigue has been modelled by the use of strain-life curves instead of the traditional stress-life curves (Mitchell, 1979). It was stated that the combination of corrosive conditions and low cycle fatigue is not well researched.

It was generally assumed that the mechanical damage from high stress will far outweigh the damage from corrosive attack. However, some researchers [Endo and Komai (1968); Endo et al (1972); Rie and Lachmann (1983)] have experimented different plain carbon and low alloy steels and aluminium alloys in salt water.

They showed that the low cycle fatigue life is shorter in salt water than in air and that the life length is dependent on the cyclic frequency and the cyclic waveform. This kind of behaviour is well established in the high-cycle fatigue system where the lives are higher than 100,000 cycles and stress and strains are predominantly elastic.

Bernstein and Loeby (1988) conducted low-cycle corrosion fatigue tests under strain control in salt water on an aluminium alloy, and stainless steel. The specimens were axially loaded and tested in strain control. It was found that the materials presented a significant reduction in life because of corrosion fatigue in the low-cycle fatigue system.

Recently, it has been recognised that stable mode (I) fatigue crack propagation can take place in notched plates of ductile and brittle materials subject to fully compressive far-field uniaxial cyclic loads (Aswath et al 1988). And they attempted to explain the effective of stress state, plastic strain, compressive overload, crack closure and load range on the mechanics of crack initiation and growth from notched under far-field cyclic compression. From their study they reached to following conclusions:

- The amplitude of the first compression cycle plays a strong role in effecting the total distance of crack growth under far-field cyclic compression.

- The crack growth rates, closure levels and crack arrest distance are controlled by the amplitude of residual tensile stresses induced upon unloading from the very first compression cycle.

Types of tests for fatigue

To determine the fatigue life of a material the researchers used many types of tests. The most common test, which applies a rotating-beam test in which the specimen is subjected to compression and tension stresses of equal magnitude while rotating, test sketch of the specimen. The R. R. Moore reversed-bending fatigue test is shown in Figure (3).

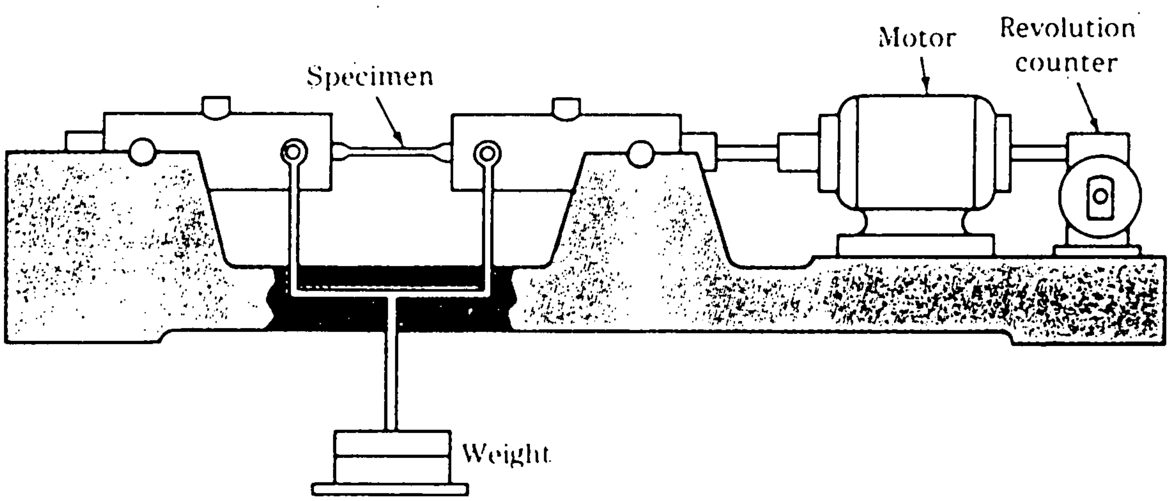


Figure (3)
Schematic diagram of an R. R. Moore reserved-bending fatigue test machine

Fatigue and weld joints and Composite Materials

Investigation of Fatigue for Weld Joint Metals

There are two matters in the fatigue consideration of a weld joint, first, is fatigue behaviours of the weld joint and the second, is the application of these behaviours to design.

Fatigue life evaluation at welded joints is an important research area, since many fatigue loaded structures are fabricated by welding. In the welded joints, the fatigue life forecasting has been suggested (eg see Lawrence et al 1978; Usami et al 1970).

Using strain-controlled fatigue data have been produced for a variety range of engineering structures, particularly in the low-cycle, fatigue life process.

The relationship between cyclic plastic strain and fatigue life has been well documented (see Landgraf 1970; Hatanaka and Fujimitsu, 1986) concerning strain-controlled fatigue behaviour of weld metals. However, it is recognised as one of the significant problems of fatigue design.

Itoh and Kashiwaya (1989) investigated low-cycle fatigue properties of steels and their weld metal. Specimens used in this investigate were taken from multi-pass weld metal deposited by shield metal arc welding and gas metal arc welding. Results obtained from this study were as follow:

- There is a trend toward reduction in the low-cycle fatigue life of weld metals as compared with the base metals.

- The primary contributor to losses in fatigue life of the low carbon steel weld metals is the lack of uniformity of the multi-pass weld, that is confirmed by hardness measurements.

- The ductility reduction of type 308 weld metals leads reductions in low-cycle fatigue life.

- The fairly accurate calculations for low-cycle fatigue life of weld metals are obtained through the use of local strain concept and Manson's universal slop system.

Fatigue Crack Propagation in Weld Area

The fatigue crack propagation behaviour of some stainless steel weldments in an air environment at 5 temperatures between 24 ^{o}C and 649 ^{o}C was studied by James and Mills (1987).
In this study also the equations of fatigue crack growth rate were developed for each of the evaluated temperature. Most of the weldment specimens were fabricated using the submerged arc welding (SAW), but few were fabricated with the gas tungsten arc welding (GTAW) process. They reached to the following conclusions:

- Fatigue crack growth rates in the air environment increased with increasing experimental temperature.

- Comparison their results with the previous results on wrought type 316 suggests that fatigue crack propagation rates in the submerged arc (SA) weldments are lower than those in type 316, while the rates in the gas tungsten arc (GTA) weldments are nearly same to those in type 316.

- Fatigue crack growth rates in a GTA weldment at 538 ^{o}C where somewhat higher than those in a SA weld at the same conditions.

A number of comparative studies (see for example Shahinian and Smith 1972, Shahinian 1978) have shown that, normally fatigue crack growth rates in austenitic stainless steel weldments increase with increasing temperature in an air environment. The fatigue failure of weldment consists of two phases:

- Fatigue crack initiation phase.

- Fatigue crack propagation phase (eg Zheng et al 1991)

Depending on the structural details, the crack can start at weld toe, the weld discontinues at other areas of stress concentrations (Lü et al, 1993). The crack will then propagate into the weld metal or base metal (see also Zheng and Sui 1989; Lü and zheng 1992). The role of fatigue crack initiation and fatigue crack propagation depends on the welding quality and structure details (Zheng and Sui, 1989; Lü et al, 1993).

Fatigue crack initiation should not be ignored in life prediction if there is no evidence of crack-like discontinuous in the structures (Lü and zheng 1992).

Stress concentration can be seen in notch components (eg a weldement). The stress cycle starts with the formation of a critical crack notch which can be predicted by the local stress-strain approach (Lawrence and Mazumdav 1979, Coffin and Jr 1978, Bhugan and Vosikovski 1989) cited by Lü et al (1993).

The assumption is that the stress cycles needed to start with a fatigue crack at the notch tip, which is equal to the life of a smooth specimen under cyclic strain control if this specimen has the same stress or strain background as the material at the head of the notch (see Coffin and Jr 1978; Lü et al 1993).

In this case fatigue notch factors (K_f), cyclic stress-strain curve, and fatigue life under cyclic fatigue strain control for the material at the notch must be looked at before fatigue crack initiation life prediction. However, it is difficult to determine accurately such data for material at some fatigue cracks initiated like the weld toe.

The influence of different parameters on the accuracy of the local stress-strain approach was reviewed by Bush (1989), and Forrnan (1972) who Initially measured the fatigue crack initiation life of materials with a notched specimen, reporting that it correlated with the maximum elastic stress range at the notch root. Mathematically this can be expressed as:

$$\Delta\sigma_{max} = K_t * \Delta S = \frac{2}{\pi^{1/2}} * \frac{\Delta K}{\rho^{1/2}}$$

where:
K_t = The stress concentration parameter.
ΔS = The nominal stress range.
ΔK = The apartment stress intensity factor.
ρ = The radius of the notch tip.

It is now easier to determine fatigue crack initiation life in different locations of welds by applying the notched specimen. The fatigue crack life derived from the above formula can be directly ultized in the life prediction of structural engineering components. Paris's law is usually applied for fatigue crack propagation rate (eg Lawrence Jr 1978): cited by Lü et al (1993) in welded specimens. This can be expressed as below:

$$da/dn = C\,(\Delta K)^m$$

It has been confirmed as the mechanism to set up the fatigue crack (1-2 mm) depth at weld toe surface occupies around 55-90% in the total life of field welds (Smith and Smith 1986, Zheng et al 1991; cited by Lü et al 1993).

Lü et al (1993) showed that the main part of the fatigue crack propagation life of welded component may often be located in near threshold crack growth. However, Pairs's law cannot be applied for the prediction of fatigue crack propagation rate in the near threshold area.
Eventually, a mathematical expression is needed that gives a satisfactory level of prediction of fatigue crack propagation rate in the near threshold area. This is helpful in the damage tolerance design of welded specimen components Ohta et al (1987): cited by Lü (1993).

Fatigue Crack Initiation in Butt Joint Welds Area

Lü et al (1993) have examined the fatigue crack initiation of the base metal, weld metal and weld interface of butt joints weld of an ultra high-strength steel. They proposed a formula for predicting fatigue crack initiation and propagation which is well correlated with experimental data. This research indicate that post weld isothermal quenching treatment improves not only the micro-structure but also fatigue resistance of weld.

Although a difference was found in the fatigue crack initiation resistance of base, weld metal and weld interface, However, a microstructure effect on the fatigue crack propagation rate was observed. It was also found that in the near threshold region, the fatigue crack growth propagation rate of the weld interface was larger than the base metal but smaller than the weld metal. The discontinuous on the notch area had an important effect on the fatigue crack initiation of the weld. It was recommend that the results from the fatigue crack initiation life experiment and fatigue crack propagation rate must be appropriately selected based on the fatigue crack initiation location and fatigue crack propagation in the weld structure.

Effect of Welding on the Fatigue Crack Propagation in a Structural Steel

Rading (1993) studied the effect of welding on the rate of fatigue crack growth in a low-carbon structural steel.

The experiment was made on the base metal (BM), heat affected zone (HAZ), and weld metal (WM). Both the near threshold and midrange process of crack propagation were investigated. the following conclusions was made from his study:

- In the midrange of fatigue crack growth (FCG), the FCG rate is highest in the heat affected zone and lowest in the metal weld.
- The increase in the fatigue crack growth rate through the heat affected zone may be due to the formation of nitrides, and hydrogen embrittlement in the heat affected zone.
- The reduction in the fatigue crack growth through the weld metal was because of residual stresses and weld micro-imperfections, which cause to change in crack tip morphology.
- The threshold stress intensity range increased in the order BM< HAZ< WM.
- The greater resistance of the heat affected zone and weld metal to near threshold fatigue crack growth was because of the coarser grain structures in these areas.

The fatigue strength of fillet weld joints is a great problem for structural designers. The stress concentration at the fillet toe, with or without undercut, is the principle factor for crack initiation under the cyclic loading. After the initial steps of crack growth, the crack propagates into the far-field stress areas.

Fatigue Crack Propagation in Fillet-Welded T-Joints

Tsai et al (1991) studied crack growth behaviour in a two-dimensional welded T-joint by using fatigue analysis. The reason for using T-joint in this study was for widely used connection in many structures. The geometric factors were weld size, initial crack orientation and unsupported flange length. Crack propagation direction was predicted using the minimum strain energy density factor theory. The following conclusions was made from there study:

- Crack growth initiates at the preferred stress concentration site in a weld joint depending on the loading, flange flexibility conditions and the fillet weld size.

- Crack growth paths start from many sites converge to a constant path in the far-field stress area.

- Notched T-joints have reduced fatigue strength because of the increased notch effect during the crack initiation stage.

Fatigue Crack Growth of Laser Beam Weld Area

Laser beam welding (LBW) was used recently in the vehicle structures, which has been shown to offer higher speed, greater precision and flexibility when compared with spot weld. While great attention has been focused on studying this process, there is an urgent need to understand the effects of weld discontinuity for example poor joint clearance, weld underfill.

Wang and Davidson (1992) demonstrated that computational modelling can be a useful tool in understanding weld discontinuity-fatigue property relationships. From their study the following conclusions can be made:

- Bead width (root penetration) has great effect on the fatigue life of a laser beam weld, with life increasing as the bead width increases.
- An increase in the joint clearance between sheets would result in a significant decrease in fatigue life.
- The formation of underfill decreases the fatigue life. The decrease in fatigue life is more pronounced as the gauge of sheet is increased.
- The fatigue life of a laser beam weld is calculated by a balance between the effects of joint clearance, underfill and root penetration.
- Fatigue of a laser beam weld is dominated by crack propagation.

Life Enhancement in the Aircraft Manufacturing Process

In the recent years, high-performance military aircraft have begun to use life enhancement techniques in the manufacturing process. For example they used shot peening, hole cold expansion, and interference fasteners in order to achieve the design life.

Fatigue life was enhanced by factors up to approximately 10 or more in the earlier research (see Schwarmann, 1983; Peasson-Smith and Potter, 1984: cited by Finney 1993), though factors of 2-5 are more common (eg Mann et al, 1978; Moore 1970 cited by Finney 1993).

It is commonly supposed that the life improvements arise from the resultant compressive residual stress field surrounding the plasticity expanded hole, causing to a reduction in the mean fatigue stress level in the local areas where cracks eventually start.

In the aircraft industry, clamping forces via fastener torques are commonly standardised. However, that a reduction can be gained by the use of the interference fit fasteners, a common approach for improving fatigue life. Interference fit will give a pre-loading effect which, though increasing the mean fatigue stress at the point of maximum stress concentration at the edge of the hole, decreases the alternating parts of the stress and hence the rate of relative movement.

Study by Finney (1993) described an experimental examination of the influence of fastener interference on the fatigue life of multi-layer aluminium alloy with cold-expanded holes. Shown the possible role of fretting and its dependence on the degree of relative movement, which is depends on the load transfer behaviours of the joint, low-load-transfer and 100% load-transfer was examined in this study. The following conclusions has been made from this study:

- The influence of hole cold expansion in enhancing fatigue limit is clearly dependent on the amount of load transfer in the joint. For example, in case of low-load-transfer metals a life improvement factor was 4, but in case of 100% load-transfer metals the improvement factor was totally ineffective.

- By using of interference-fit fasteners extended the fatigue life of load-transfer metals by a factor of about 6 and was independent of the amount of interference. Moreover, with 100% load-transfer metals the life improvement depended on the amount of interference, being ineffective at 0.5% but progressing to a 5-fold increase in life at an interference of 3%.

- By using the combination of cold expansion and fastener interference lead to an improvement in life in low-load-transfer metals by a factor of about 6. And by 100%-load-transfer metals the factor ranged from 5 to 40 and increase with degree of interference.

Fatigue Creep and Cavitations

The importance of cavitation in creep and creep fatigue damage analysis has been considered (eg see Hull, 1959; Gittus, 1967). Studies of creep damage have proceeded historically along two levels, basic and empirical.

At the first level, significant progress has been made towards an understanding the mechanism of growth equilibrium-shaped cavities by grain boundary diffusion (Hull, 1959; Speight and Harris 1967).

The integrated effects of power law creep and grain boundary diffusion on cavity growth have been recognised by many workers (eg Speight 1967; Needlman and Rice 1980).

In all proposed models a fundamental assumption is that a fixed number of regularly spaced cavities are nucleated at all grain boundary planes normal to the tensile stress direction at one time. However, empirical investigations of cavitation have shown that cavities are continuously nucleated during the test (Can and Greenwood, 1979), and that cavity distribution is specially heterogeneous.

Generally, both these phenomena have significant repercussions on cavity growth rate and life forecasting's. In contrast to cavity growth, the mechanism of cavity nucleating in engineering materials is not yet clear.

Majumdar (1989) examined the relationship of creep, creep fatigue, and cavitation damage in type 304 Austenitic stainless steel. He declared that the creep damage is to be a highly in homogenous phenomenon, both in space and in time.

Furthermore, it was discovered that a small fraction of boundaries are so intensely cavitated by a bout 10-25% of life for all purposes which can be considered cracking process. Other similar boundaries, which are similarly oriented with respect to the tensile stress direction, however, are nearly devoid of cavities at the end of life.

The early nucleating of cracks by creep mechanism has an important effect on creep-fatigue interactions, especially for experiments at low strain ranges. A simple ductility model represents to be able to account for the early crack initiation. Tests at higher strain ranges also/or in shorter hole times rang may not achieve their complete potential ductility due to their lives are cut short by crack propagation.

Fatigue in Composite Materials

Composite materials have been used for many engineering materials and structural application. Modern materials science aims to find and make stronger, rough and lighter material.

Fatigue damage in centrally notched graphite/epoxy (Gr/Ep) laminates subjected to tension-tension (T-T) constant stress values at room temperature and low humidity was investigated by Jen et al (1990) in order to measure S-N curves, failure surfaces, crack lengths and their corresponding growth directions, delamination areas and transverse delamination length. From their study they reached to the following conclusions:

- The pre crack metal have shorter fatigue life.
- The crack-growth rate predicated by the Pairs law can be modified to apply to the effective transverse delamination length.
- Stiffness reduction was observed to be a power of applied cycles.

Experimental Work

Aim of the Experimental Work

- To measure the energy absorbed during Impact-Test by different Materials (Aluminium and Mild Steel).

- To study the effect of Temperature, Shape of Notch, and Depth of Notch on the amount of energy absorbed during Impact-Test.

- To study the effect of Heat-Treatment on the Mild-Steel specimens.

Materials Used

- Experimental work was done on the most common extrusion Aluminium alloys 6060, which it is characteristics are shown in the Table (1).

ALLOYING CHARACTERISTICS

EXTRUDED AND DRAWN PRODUCTS

Alloy	Typical Application (√)	Forms Available						Characteristics					
		Extruded				Drawn							
		Rod & Bar	Solid Shapes	Hollow Shapes	Tube	Rod & Bar	Tube	Corrosion Resistance	Machining	Anodising	Forming	Welding	Heat Treatable
1200	Commercially pure aluminium. Used where formability, not strength, is important.	√	√	√	√	√	√	A	DC	B	AC	A	
1350	Used for electerical conductors.	√	√	√	√	√	√	A	DC	B	AD	A	
2011	Commercial machining alloy. Used as feed stock for maching	√	E			√		D	A	D	CD	D	√
2014	High strength alloy used for aircraft structures and heavy duty structures.	√	E					D	B	D	CD	C	√
5083	High strength alloy used in transport, marine and general applications where welding is of major importance.	√	E					AC	CB	C	AC	A	√
6060	The most commonly used extrusion alloy. Used for all architectural applications, light duty structural framework. Can also bechemically brightened for moulds and trims.	√	√	√	√	√	√	A	C	A	AC	A	√
6061	A structural alloy used whre strengh and corrosion resist-ance are required.	√	√	√	√			A	BC	B	AC	A	√
6101	Combines strength and high electrical conductivity.	√	√	√	√	√	√	AB	BC	A	AC	A	√
6106	A medium strength alloy. Used for Architectural applications where additional strength is required and for structural applications not involving welding.	√	√	√	√	√	√	A	CB	A	AC	A	√

Figure (1)

Table shows characteristics of the most common extrusion Aluminium Alloys 6060

Also Mild Steel with three different types of heat treatment was used during experimental work, which they are as follow:

- Non-Heat Treatment Mild Steel.
- Mild Steel Heated to 900 ^{O}C, Held 1 hour, and then Furnace Cooled.
- Mild Steel Heated to 650 ^{O}C, Held 1 hour, and then Cooled in Air.

Figure (2) shows mild steel specimens before fracture.

Size of Specimens

Size of specimens was standard 10 * 10 * 55 mm for mild steel with V shape notch, and same size for aluminium but with two different shapes of notch:

- 1 mm, 1.5 mm, and 2 mm depth V shape notch.
- 1 mm, 1.5 mm, and 2 mm depth U shape notch.

Figure (3) shows aluminium specimens used during experimental work.

Size of specimens used for Tensile-Test was 182 mm long * 46 mm width * 4 mm depth one with no notch and another with 8 mm depth notch.

Testing Machines

A simple Impact-Test machine was used during experimental work, which is shown in the Figure (4).

Also Tensile-Test machine (Shimadzu) was used for tensile test for Aluminium specimens, which is shown in Figure (5).

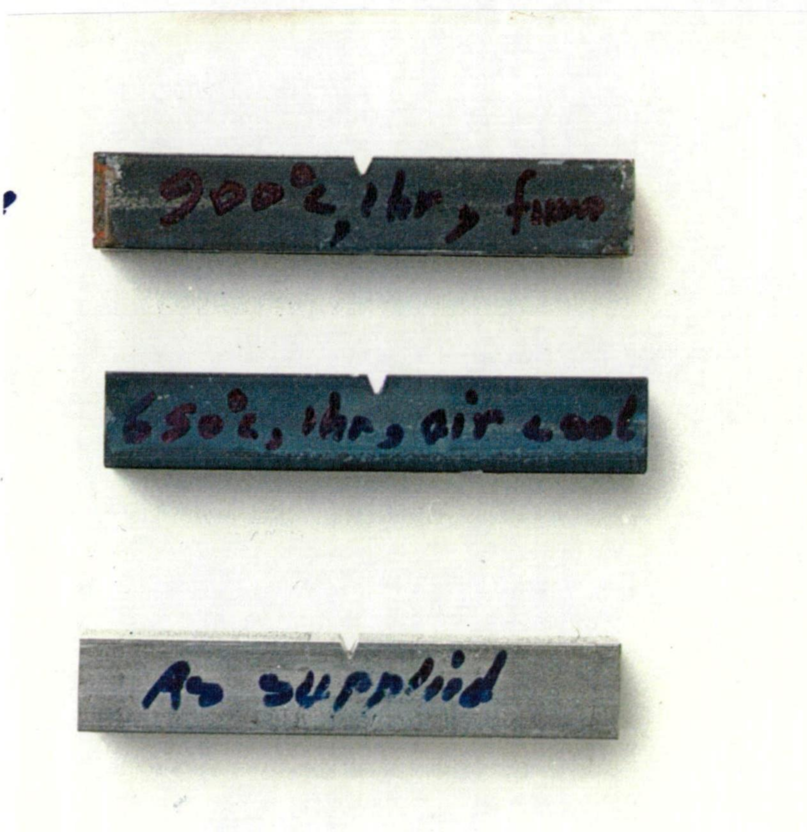


Figure (2)
Mild steel specimens used during experimental work

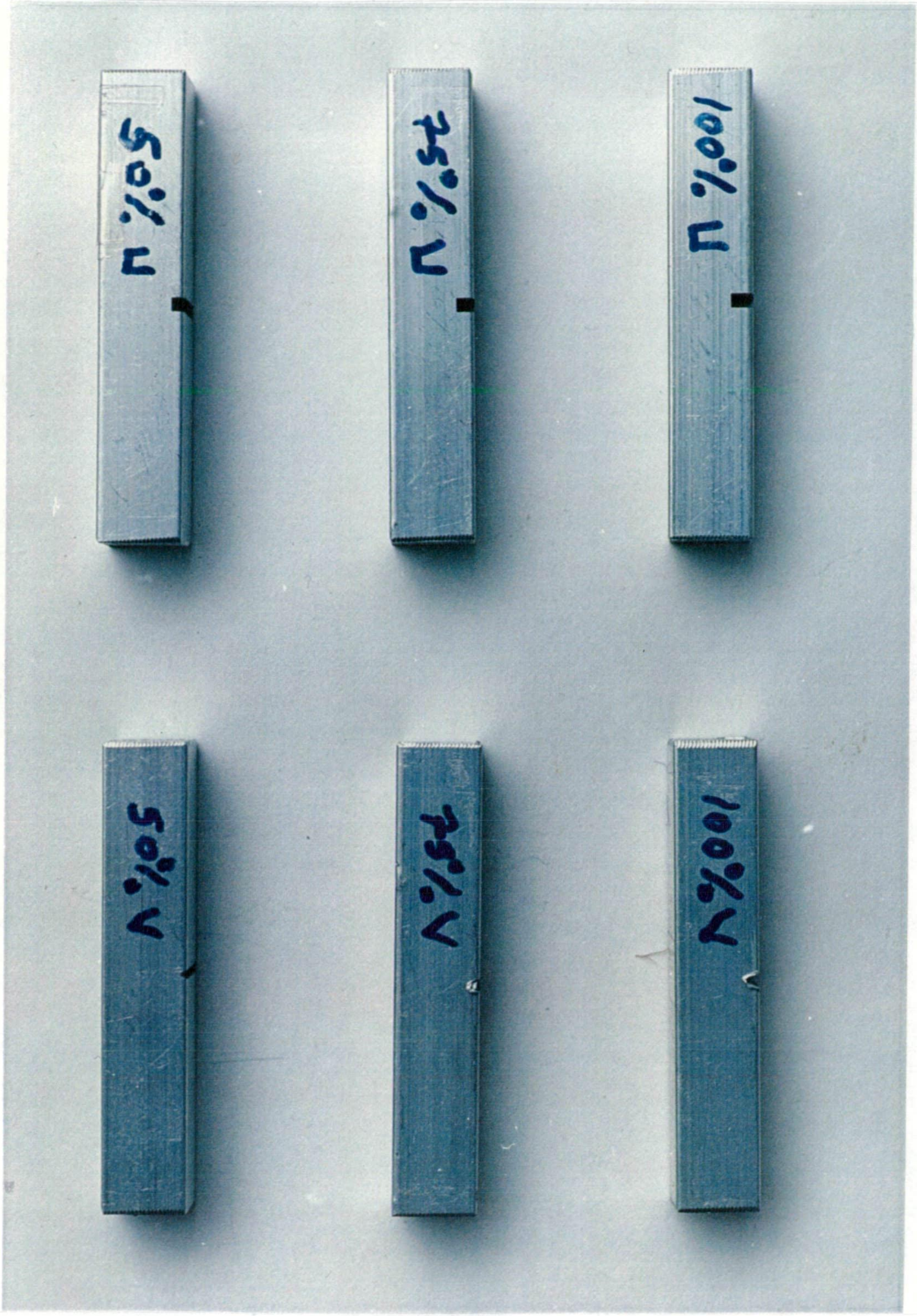


Figure (3)
Aluminium specimens used during experimental work

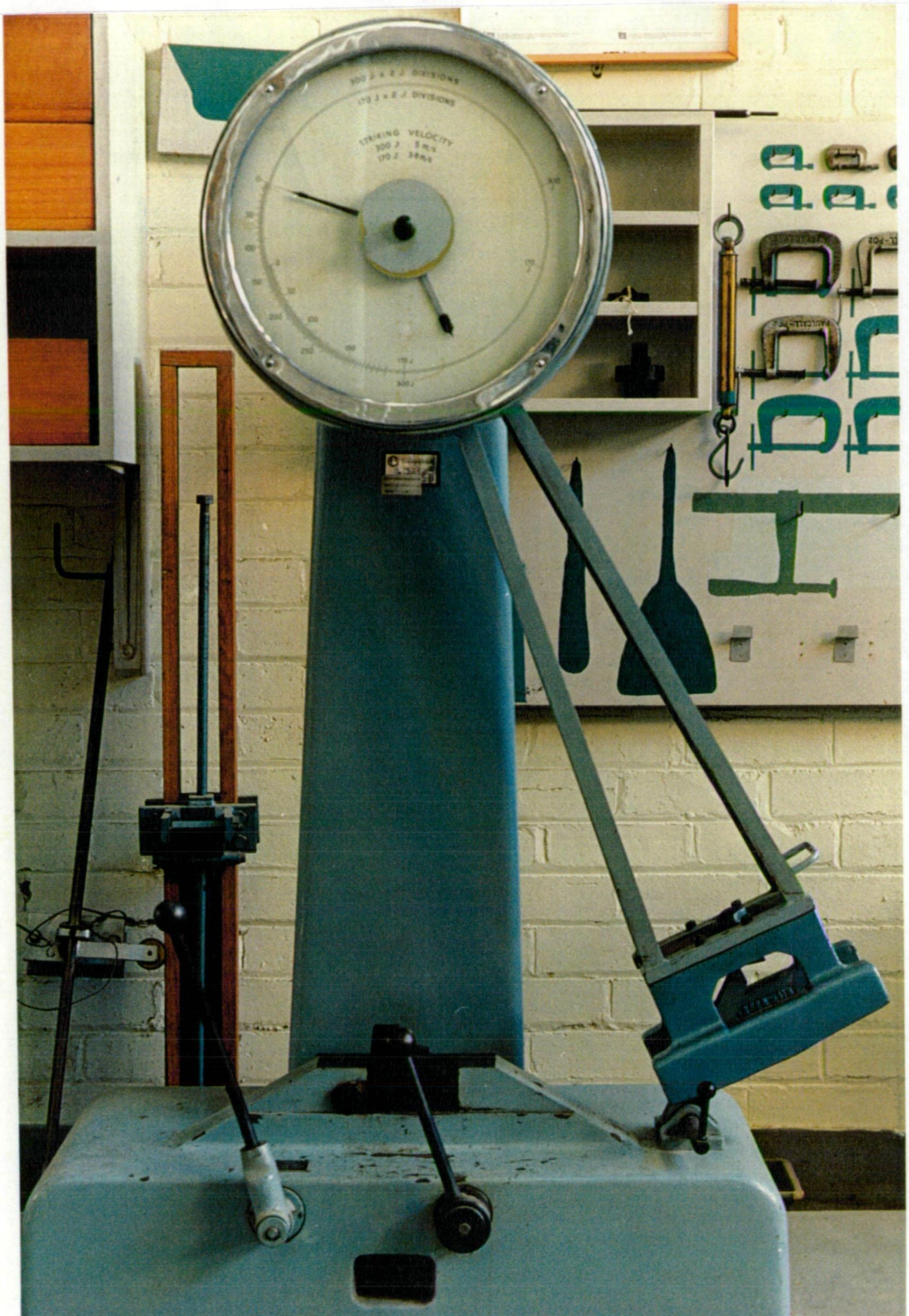


Figure (4)
Impact-Test Machine

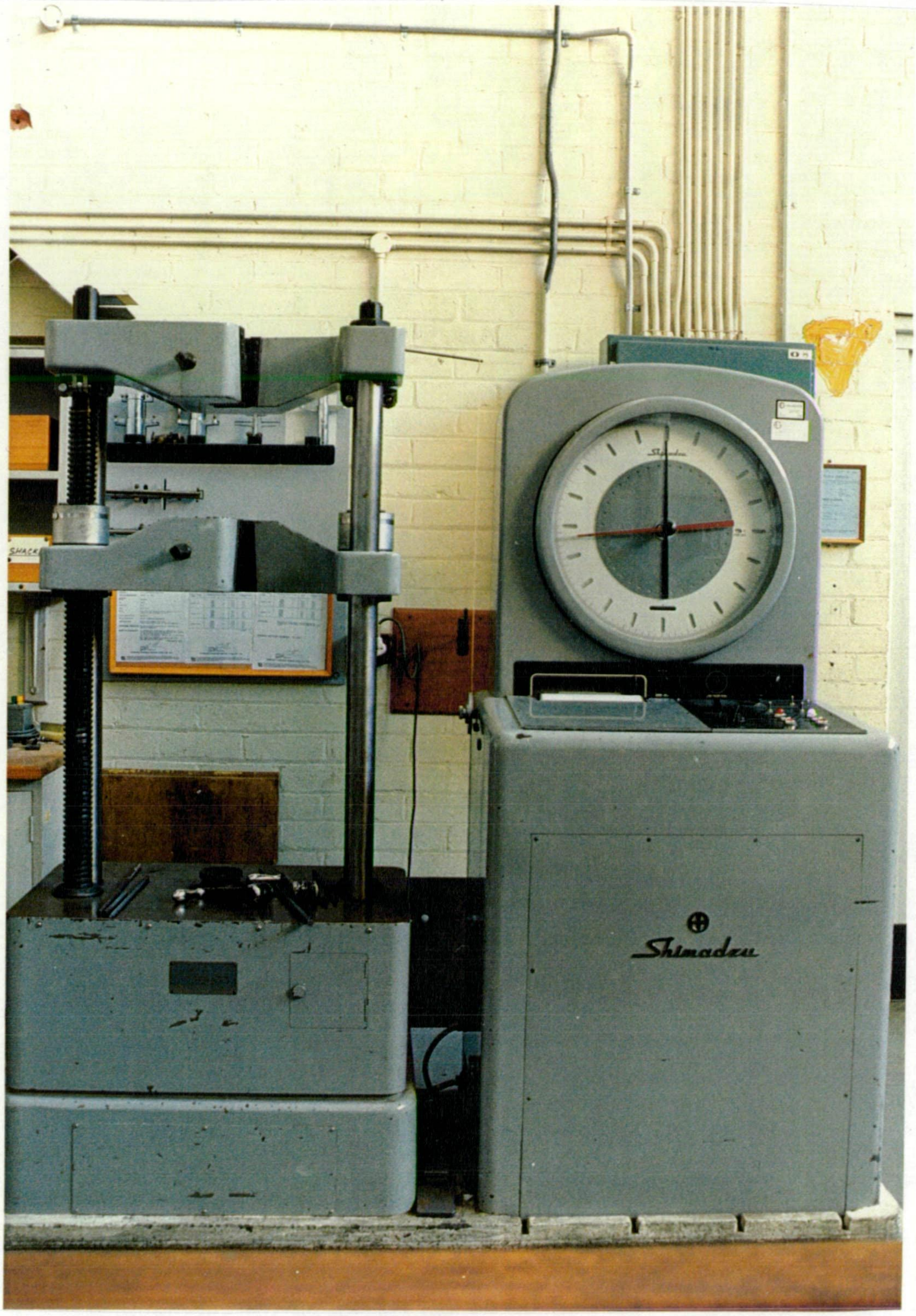


Figure (5)
Tensile Test Machine (Shimadzu)

Procedures

First procedure was to place a charpy V and U notch Aluminium and Mild Steel specimens across parallel jaws in the impact-test machine. A havey pendulum released from a known height strikes the specimen on its downward swing causing to fracture the specimen. By knowing the difference between the initial and final height of pendulum and the mass of pendulum, the energy absorbed by specimen can be calculated.

Second procedure was on the Aluminium (6060) to measure the behaviour of the Aluminium 6060 with and without present of notch. Also to measure the effect of notch on the extension load and on the elongation in the specimens before failure occurs.

Results

The following results was obtained form experimental work:

- By increasing temperature of the mild steel, the amount of energy absorbed by the specimens are increasing, which means the fractures are changing from ductile by increasing the temperature.

- For the aluminium specimens, we could not record big changes in the amount of energy absorbed by changing the temperature, which means that in Aluminium materials there is no clear transition in fracture model.

- The amount of energy absorbed was higher in the V shape notch than the U shape notch.

- By reducing the depth of the notch the amount of energy absorbed is increasing.

- The amount of energy absorbed by mild steel is increased by increasing temperature.

- The highest energy absorbed was in the orange colour specimen, and also there was a big change in the amount of energy absorbed by changing temperature. for the blue colour change was less than orange but more than in plain colour.

- The highest energy for orange colour specimen was due to the large size of the grain, which was increased by increasing heat treatment temperature.

- Clear transition in the fracture model of mild steel can be seen by changing the temperature of the specimens, which means in the same range of temperature change, mild steel has a good capability to change it's fracture model from ductile to brittle or visa versa more than Aluminium.

Figure (6) shows effect of temperature on the energy absorbed by aluminium.

Figure (7) shows effect of temperature on the energy absorbed by mild steel.

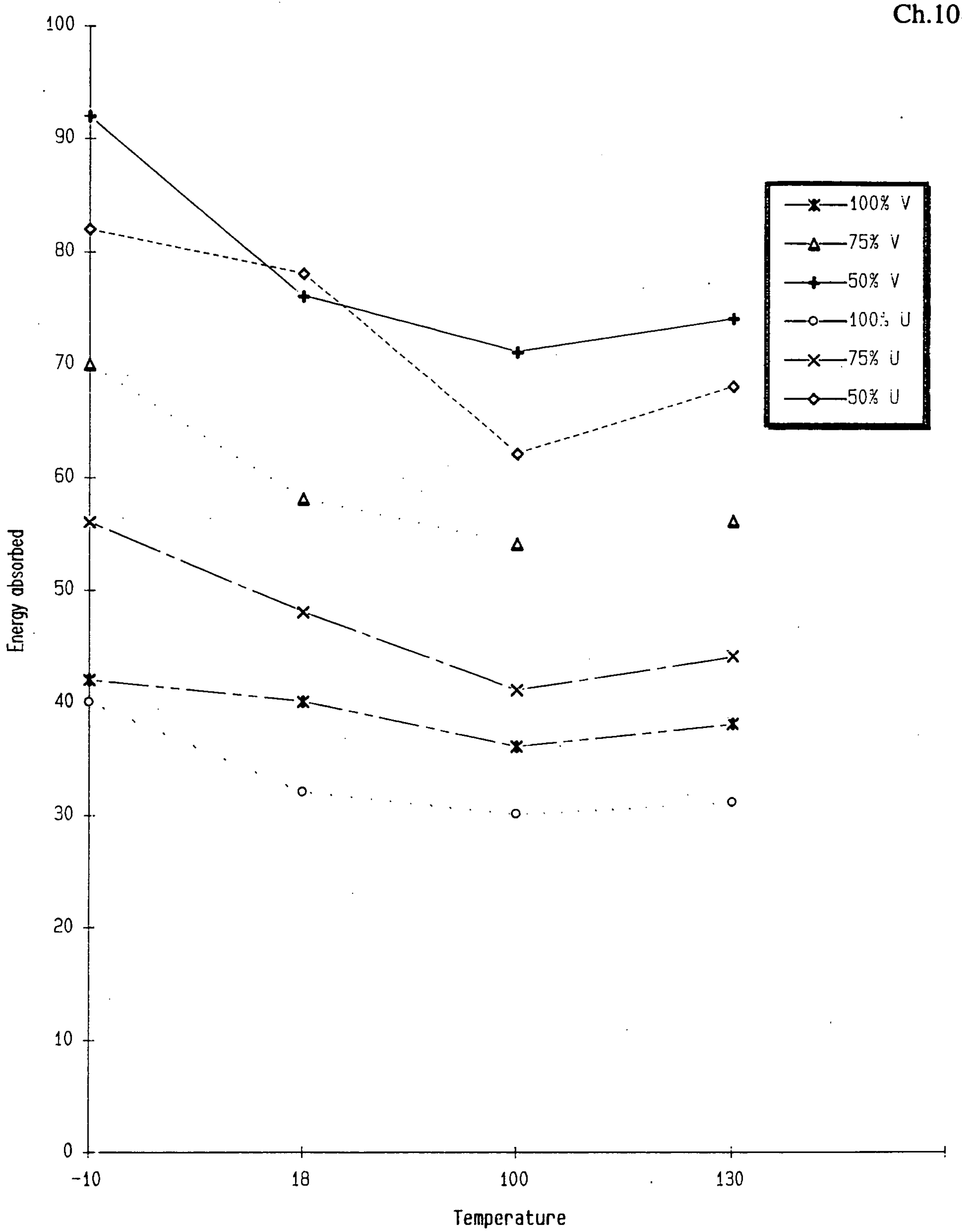


Figure (6)
Effect of temperature on the energy absorbed by aluminium.

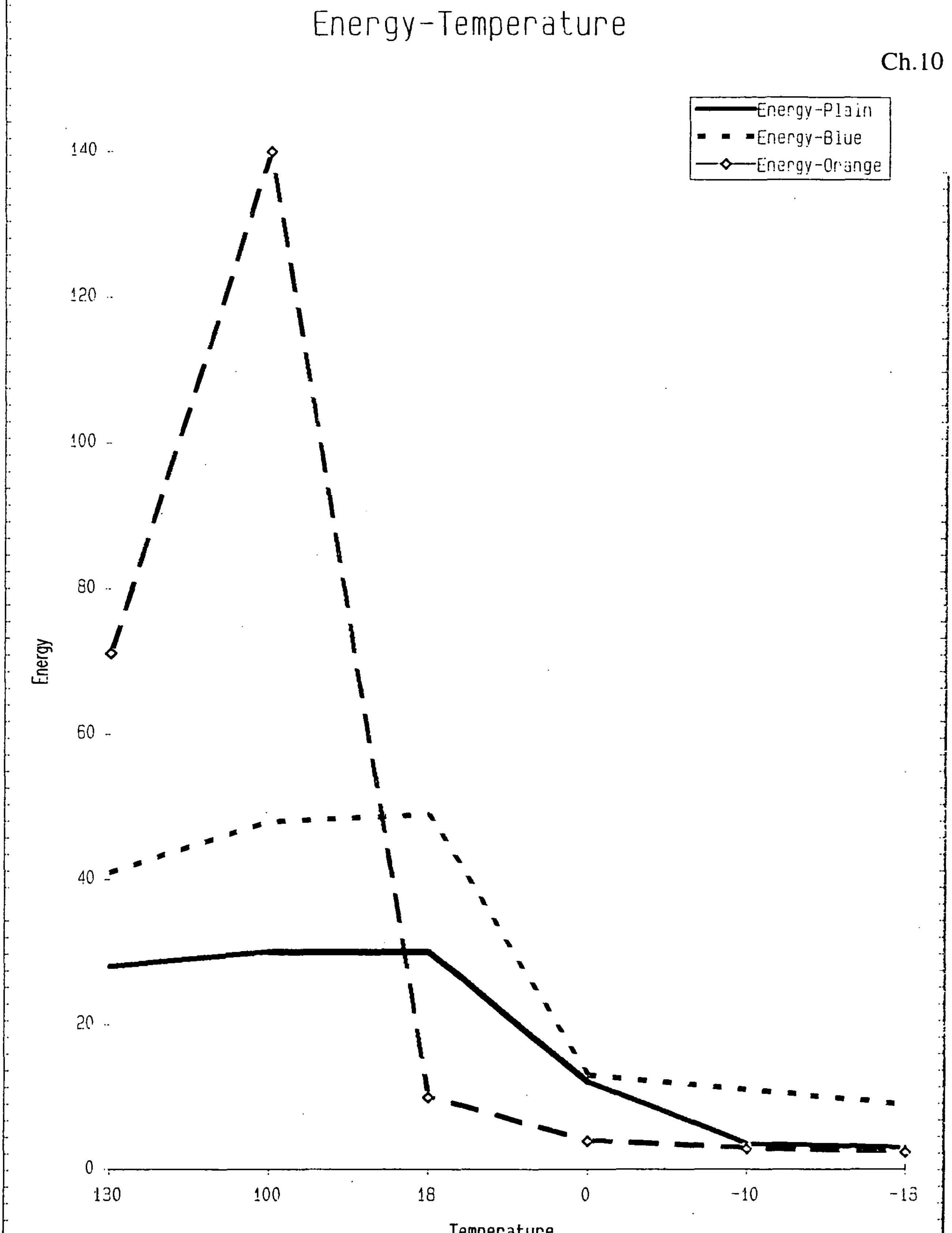


Figure (7)

Effect of temperature on the energy absorbed by mild steel.

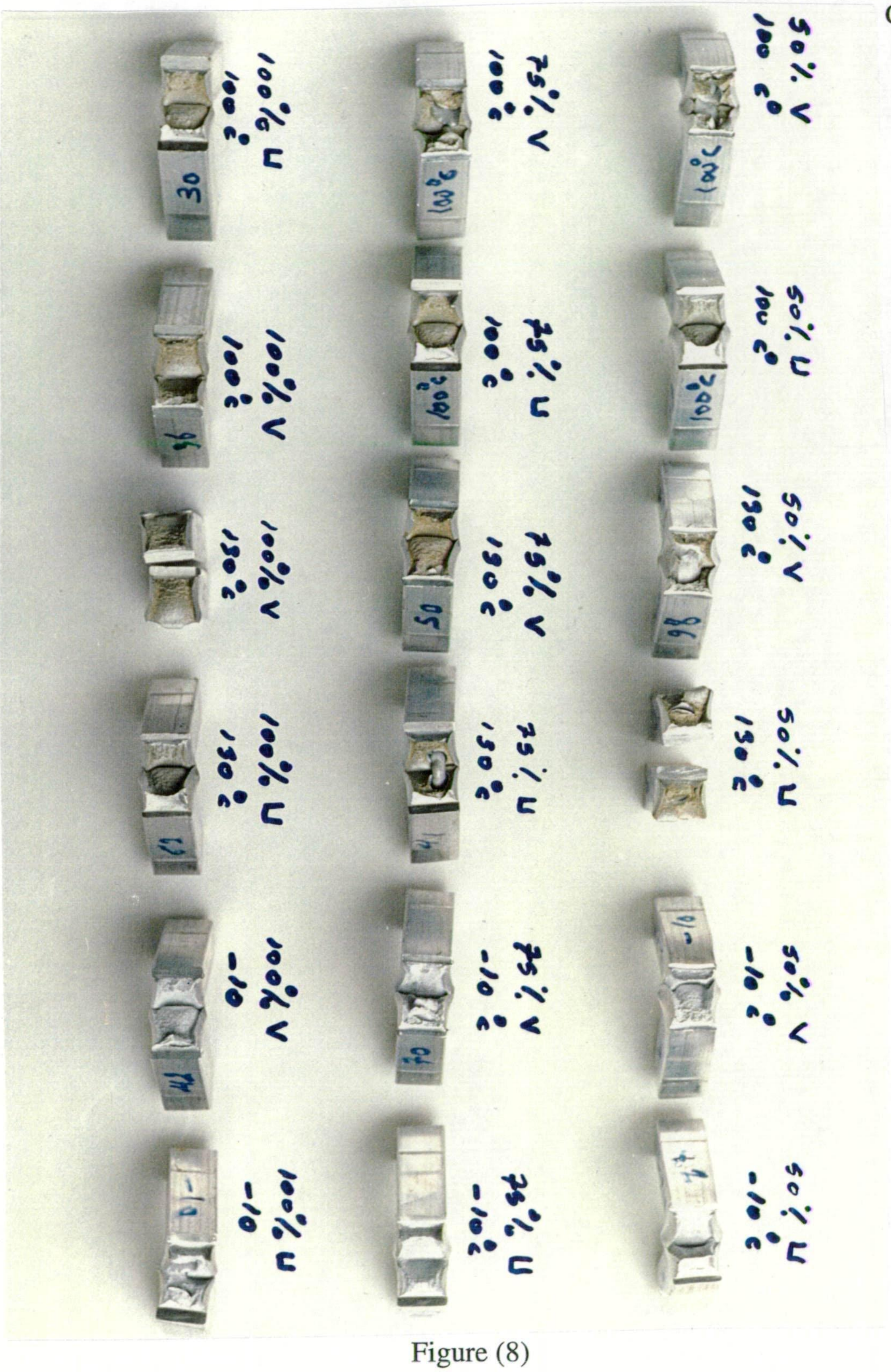


Figure (8)

Fracture surface for Aluminium specimens with different temperatures and different notches

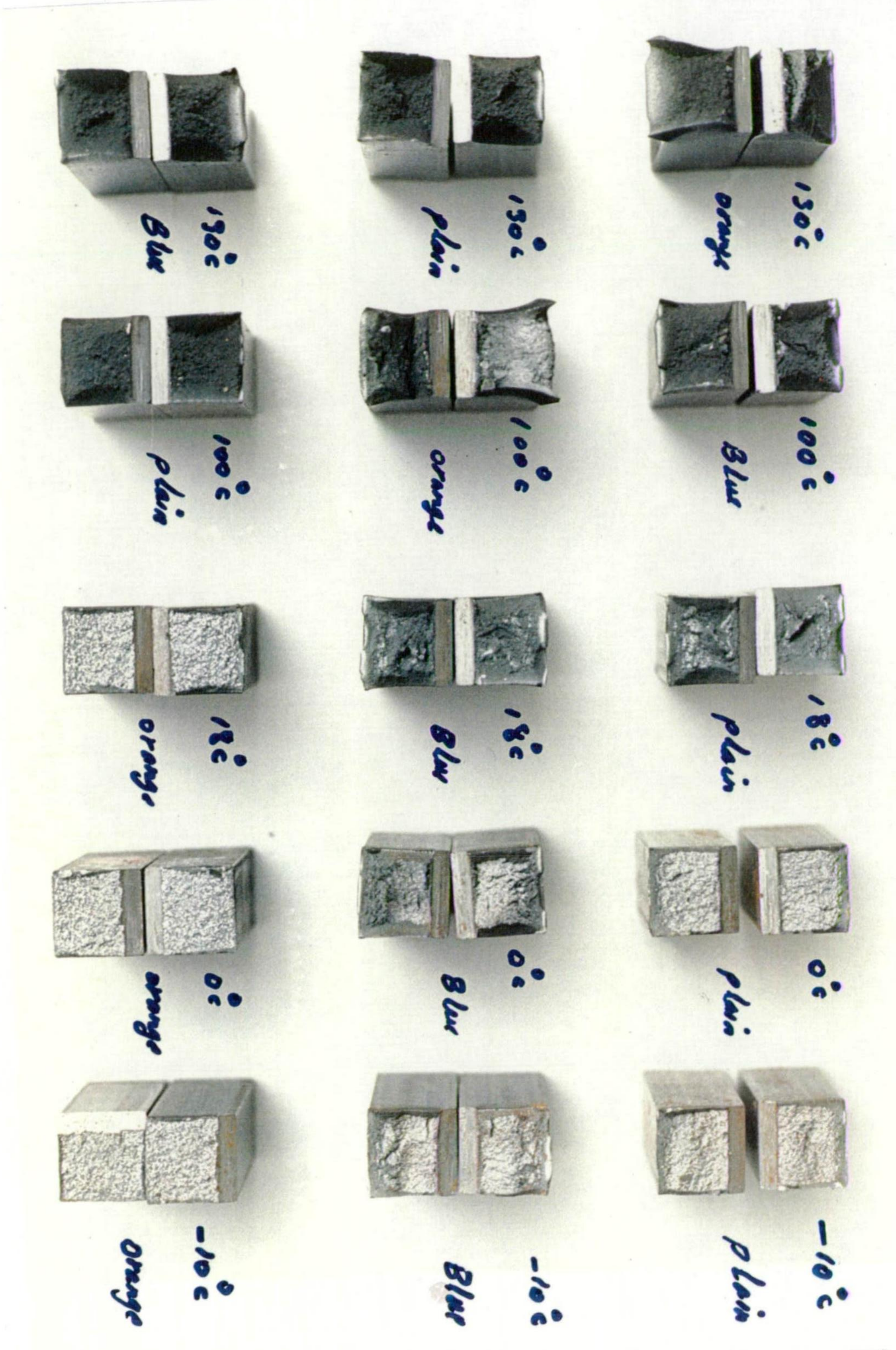


Figure (9)

Fracture surface for mild steel specimens with different temperatures

For second experimental work on the tensile-test machine, the following results were obtained:

By plotting extension load against the elongation for both specimens with and without notch as shown in the Figure (10, 11), respectively. The following results were obtained:

- Specimen with 8 mm notch broke at the load 42.50 KN. while unnotched specimen was broken at load 64.95 KN.

- There was difference in the elongation of both specimens, which was about 20 mm more in unnotched specimen.

From both results we can get:

- Parts with notch takes less time to failure occurs than unnotched parts.

- There was clear sign of elongation for the parts without notch, which can help inspector to see the change in the structure of the parts during inspecting period.

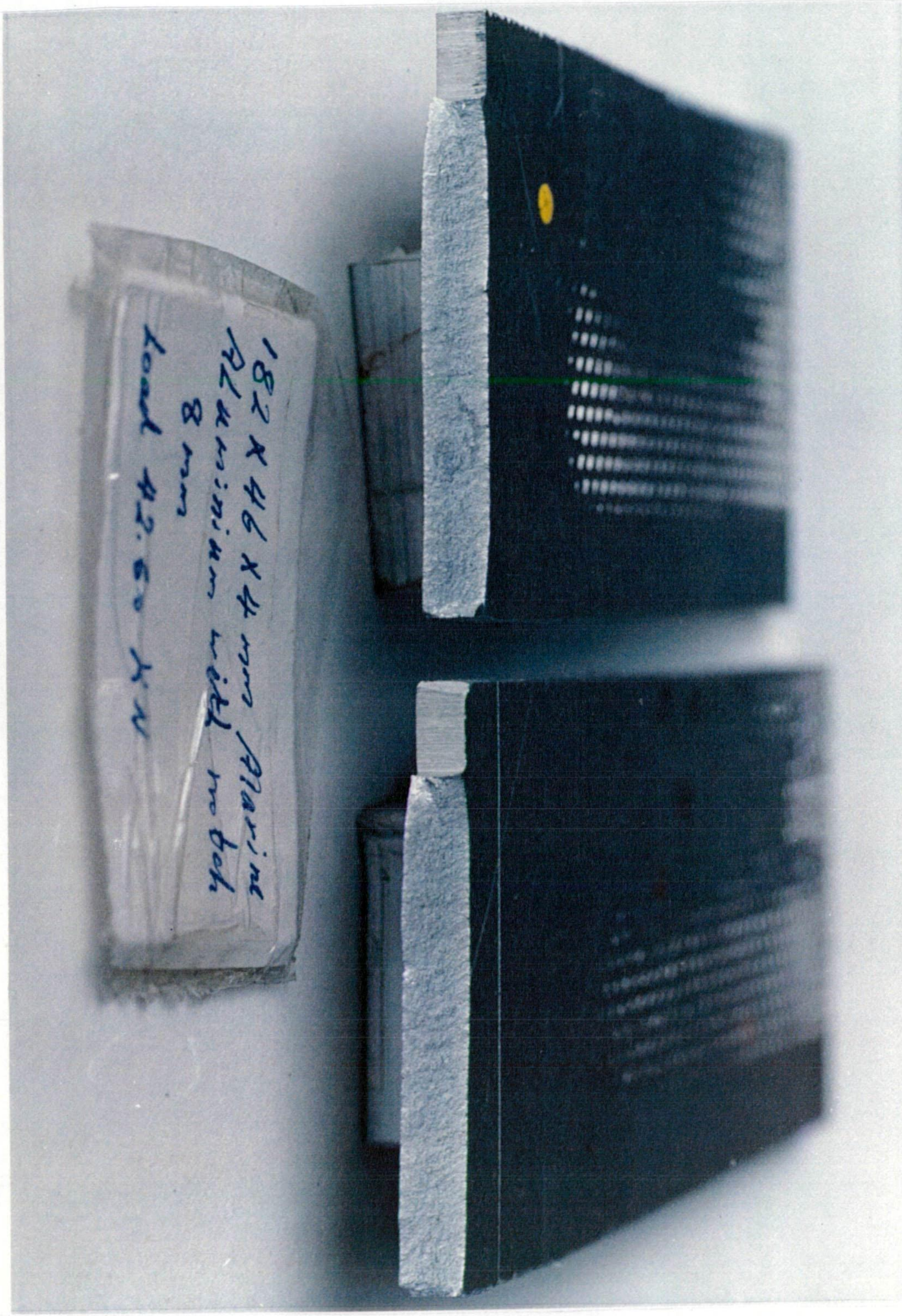


Figure (10)
Fracture surface for Aluminium specimens with notch

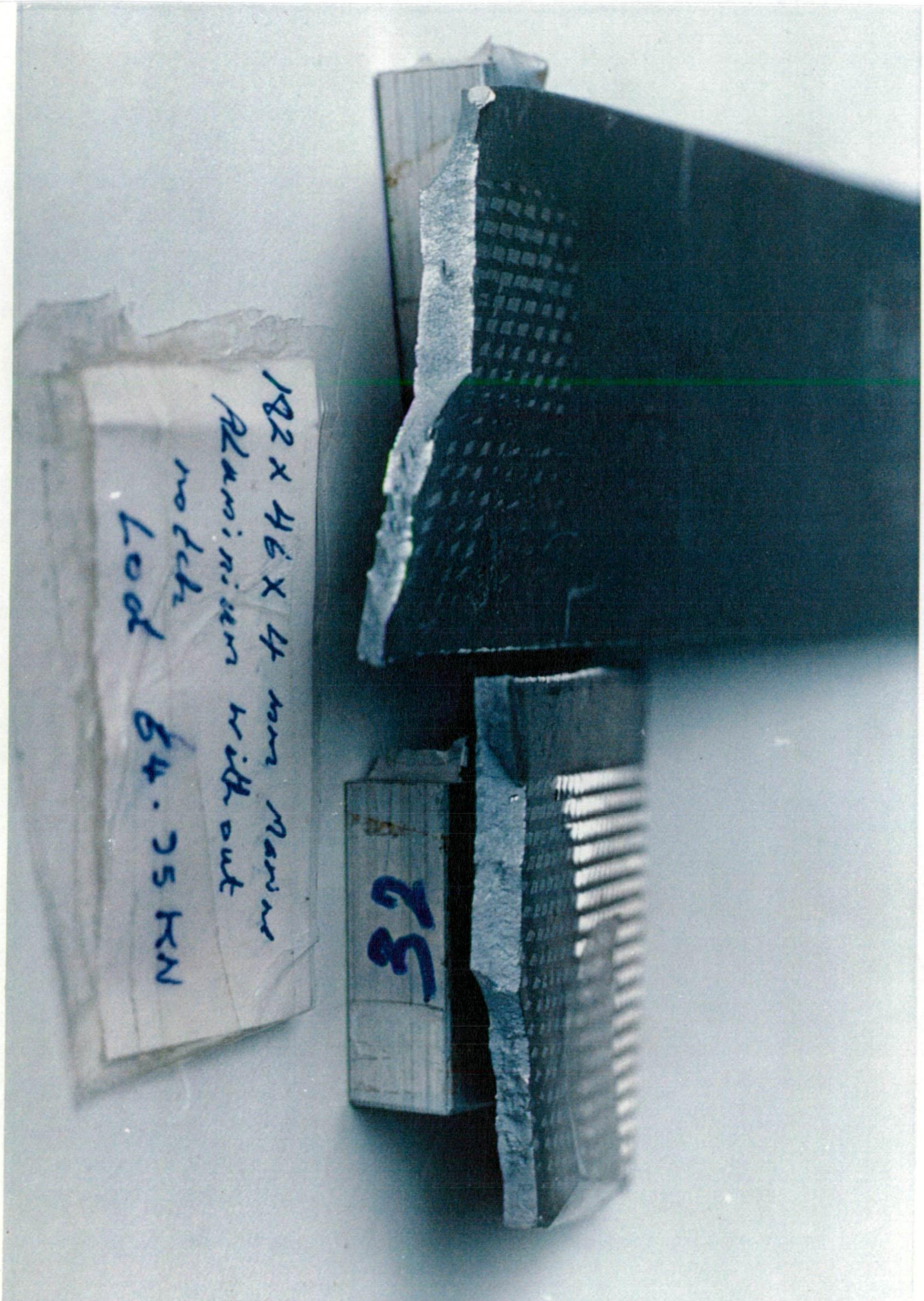


Figure (11)
Fracture surface for Aluminium specimens without notch

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